Global Climate Change and Adaptation: City of Cape Town sea-level rise risk assessment

Phase 5: Full investigation of alongshore features of vulnerability on the City of Cape Town coastline, and their incorporation into the City of Cape Town Geographic Information System (GIS).

Geoff Brundrit

oceangeoff@iafrica.com

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Contents

Glossary of terms as applied in this document

Mean sea-level: Mean sea level (MSL) is a measure of the average height of the ocean's surface (such as the halfway point between the mean high tide and the mean low tide); used as a standard in calculating land elevation.[1] Can be influenced by prevailing winds, but not tides, storms or changes in air pressure.

Still water: A measure of sea-level as it is affected by changes in mean sea level, tides and atmospheric pressure, but not by wind or waves. Equivalent to the sea-level if it were recorded within a glass cylinder, that was only open top and bottom.

Wave run-up: A function of sea depth. Occurs where there is appreciable wave height at the beach. Wave run-up affects the "water's edge".

Wave set-up: Is a function of swell height, which in turn is a function of the direction of the swell, the ocean from which the swell approaches and the orientation of the coastline relative to the approaching swell. Wave set-up determines the size of the swell at the break, which in turn affects the size (and energy) of the waves at the beach. Wave height at the break is typically three times the wave size at the beach.

Sheltered coastline: Exposed to changes in mean sea-level, but not exposed to wave set-up or wave run-up.

Exposed coastline: Coastline that is vulnerable to changes in mean sea-level and wave set-up.

Very exposed coastline: A section of coastline that is exposed to changes in mean sea-level, and because of its bathymetry, orientation and shape is also exposed to wave set-up and wave run-up.

Low risk coastline: Coastline that is sheltered, contains a geology that either absorbs or withstands wave energy without changing and does not contain valuable or strategic infrastructure or sensitive ecological habitats.

Medium risk coastline: "Exposed" coastline that contains some valuable infrastructure.

High risk coastline: "Very exposed" coastline that contains valuable infrastructure or sensitive ecological habitats.

Very big wave events: Storms with waves that exceed 10 metres in peak-to-trough amplitude.

[1] Proudman Oceanographic Laboratory

1. Introduction

The terms of reference require that this Phase 5 "improve(s) understanding of the extent and manner in which City of Cape Town's coastline is likely to be impacted by sea level rise. It is propose to achieve this by adding the influence of local factors such as offshore bathymetry, storm direction and coastal geography to the sea level rise model developed in Phases 1-4, and by including an understanding of how the various influences on sea-level rise interact with each other at a specific locations and over time."

The study is written up in two self contained reports. This, the first of the reports, incorporates ocean and coastal dynamics into the GIS model developed in Phases 1-4. The initial model relied heavily on altitude (height above sea-level) to identify the location of sea-level rise risks. This phase develops that model by adding the influence of coastal topography and geology, as well as the swell direction and the extent and nature of coastal development.

The second report integrates the findings of the first report into a coastal vulnerability assessment and proposes means of taking sea-level rise adaptation decisions so as to ensure coherence and effective prioritisation.

2. Summary of the Capabilities of the Existing GIS

The primary objective of the early phases (1-4) of this study was to model and understand the ramifications of predicted sea-level rise and increased storm events for the City of Cape Town, thereby providing information that may be used for future planning, preparedness and risk mitigation. This was achieved through a computer-based Geographic Information System (GIS), housed in the City of Cape Town Geomatics Division.

The GIS model demonstrates the potential changes to the coast resulting from sea-level rise. Variables within the model are able to be changed to accommodate variations in predictions as well as illustrating the impacts of catastrophic and combined events. The model incorporates the City's aerial photography, survey data, contour maps and overlays of the infrastructure and services. Examples of the output of the GIS inundation model for the entire City of Cape Town and for the Strand area are shown in Figures 1 and 2 below.

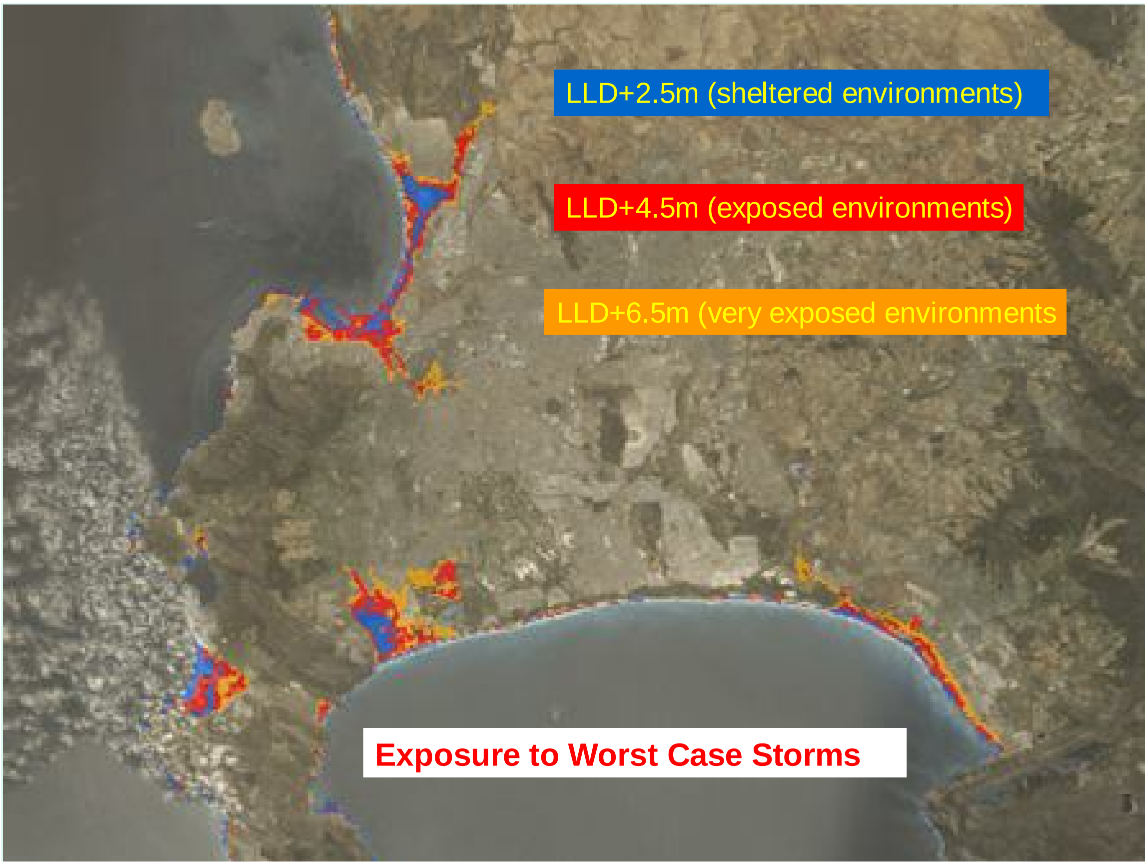

Figure 1: The exposure of the City of Cape Town to the worst case storms to be expected.

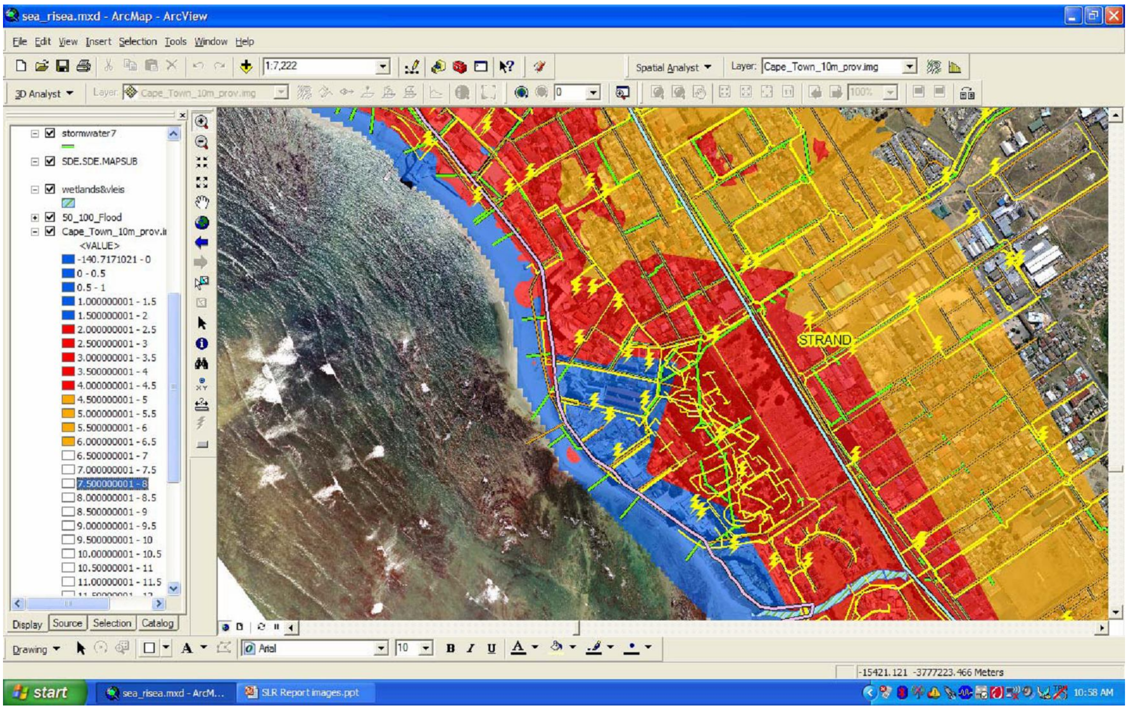

Figure 2: A snap shot image (1:7,222) of the Strand area (a low-lying area without much protection), depicting the three inundation areas used in the GIS inundation model

The nature of extreme sea level events along the coastline of the City of Cape Town was investigated through a re-interpretation of sea level records from the SA Navy Tidal Network stations at Simon's Town and Cape Town, to give extreme sea levels relevant to sheltered coasts. Where the coast is not protected, particularly on sandy beaches, the extreme waves associated with severe storms can lead to wave set-up, which needs to be added to the sea levels on such exposed coasts. When deep water is found close to the coast, the coast becomes very exposed, and both wave run-up and wave set-up need to be added to the sea level. These additional amounts can be estimated from the wave climatology derived from the wave recorder off the coast at Slangkop, and from observations of extreme storm events at the coast.

The interpretation of the extreme sea levels, and the corresponding inundation areas at risk, depends critically on the degree of exposure along each stretch of coast. All sea levels are referenced with respect to Land Levelling Datum, which is close to Mean Sea Level.

- The blue inundation area, up to LLD+2m, is relevant to **sheltered environments** along the coast.
- The red inundation area, between LLD+2m and LLD+4.5m, is the extra area relevant to **exposed coastal environments**, and

- The orange inundation area, between LLD+4.5m and LLD+6.5m, is the extra area relevant to **very exposed coastal environments.**

Figure 1 shows the extent of the three areas at risk around the entire coast of the City of Cape Town. There is a contrast between the extent of the areas at risk on the steep cliffs of the Peninsula and the lower coastline of Table Bay and northern False Bay. The vulnerability of low-lying lagoons, both existing and reclaimed is also apparent. A snapshot of a vulnerable area at the Strand, Figure 2, shows the capability of the original GIS model to illustrate the three inundation areas, and identify some of the municipal infrastructure (roads, electricity etc) that is at risk.

The actual degree of exposure relevant to each section of coast has not been incorporated into the existing GIS. Rather, all three categories of exposure are given at every section. This constitutes a limitation to the use of the GIS, and its value as an interpretative tool. The determination of the degree of exposure relevant to each stretch of coast, its incorporation into the GIS, and its risk interpretation are the principal objectives of Phase 5 of this project.

3. Influence of Sea Level Rise on the Vulnerability from Extreme Storms

Figure 1 can be used immediately to illustrate the consequences of the very worst sea level situation that can be expected at the present time. Such a situation would arise only if an extreme weather event along the coast coincided with an extreme spring high tide, a situation with a nominal return period of 500 years. Then, the blue inundation area would be appropriate for a sheltered coast, the red inundation area for an exposed coast and the orange inundation area for a very exposed coast.

Global projections of the influence of climate change on sea level, as given in studies such as the recent Assessment Reports of the Inter-Governmental Panel on Climate Change (IPCC), suggest that sea level rise over the next decade will be restricted to some 20cm. The principal influence of this projected sea level rise will be that storms will be built on a higher foundation. There will be little difference to the sea levels reached in these storms over the next decade. Thus the blue, red and orange inundation areas will remain valid. What will be different is the frequency with which the sea level of LLD+2m, relevant to sheltered areas, will be achieved at the end of the next decade, compared to present. Rather than being associated with a return period of 500 years, the return period will shorten to some 30 years. In this way the return period of high sea-level rise events is a log function of land levelling datum, and relatively small increases in sea-level (such as have already been observed) have a disproportionate effect on the frequency of extreme sea-levels.

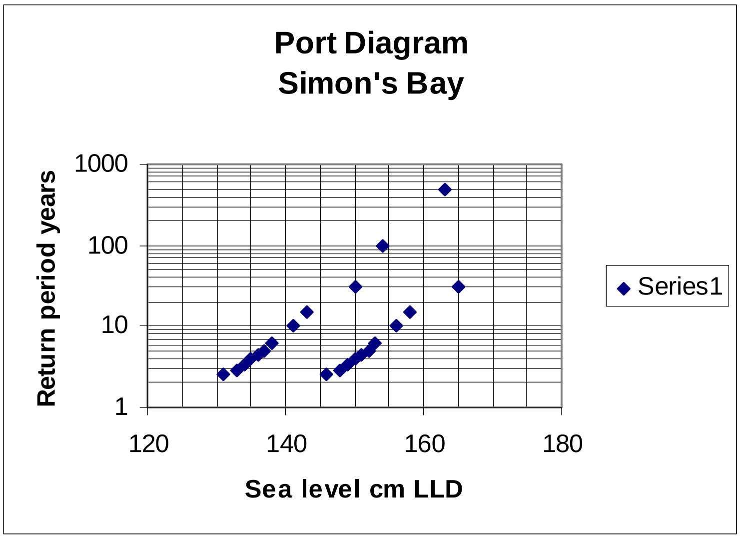

Figure 3: Extreme sea levels expected in sheltered areas at the present time, and after sea level rise of 20cm.

The blue areas all around the coast will be inundated at increasingly shorter intervals, and the risk of damage to the first line of defense will grow. The blue areas will be a valuable guide in setting out the new Coastal Protection Zone for the City of Cape Town.

An assessment of the adequacy of the present protection to the blue inundation areas all around the coast of the City of Cape Town is urgently needed. This is the first recommendation of this Part 1 of Phase 5 of the Study.

When it comes to the red and orange inundation areas marked in Figure 1, these are only relevant at those parts of the coast that are exposed or very exposed. The degree of exposure will be limited to those parts of the coast where the big storm waves are able to penetrate right up to the coast, without any appreciable dissipation. Exposure to big storms is addressed in Section 4 (below).

4. Key Directions for Extreme Storm Waves and their Characteristics in the Open Ocean.

4.1 Wave Climatology

A wave climatology for the South African coastline has been assembled from observations made by the CSIR Wave Research Group, and reported by Rossouw (1989). The wave recording site of principal interest to the City of Cape Town is referred to as Slangkop. This deep water recording site was situated 14km offshore of Slangkop lighthouse in 170m of water. A total of 11424 records of wave height at 6 hourly intervals, provided 63% coverage over the 12 years prior to 1988. These records provide the significant wave height, H_S defined as the average of the highest one-third of all wave heights in the recording interval. A statistical analysis of the significant wave heights permits estimates of the median H_S, and the expected return periods of its extreme values.

Table 1: Significant Wave Height Statistics from Slangkop 1976-1988

Significant wave height H_S	
Median value	2.54m
Value at a return period of 1 year	7.61m
Value at a return period of 10 year	9.37m
Value at a return period of 100 year	11.11m

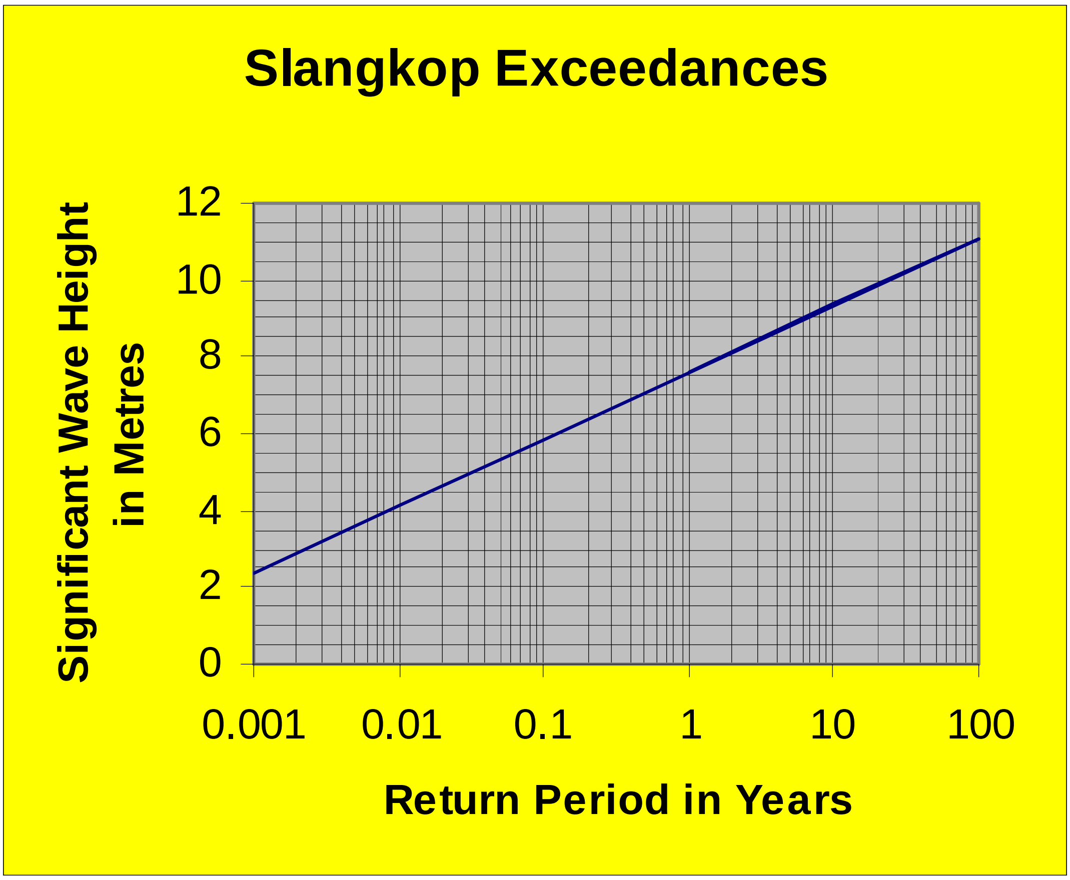

Figure 4: Significant wave height exceedances at Slangkop

The median peak period of the waves measured at Slangkop was 12.4 seconds, whilst the peak period exceeded 15.5 seconds for 10% of the time.

The wave recorder in use at that time did not record wave direction. In order to obtain directional data, the records from Voluntary Observing Ships were used. This data was obtained intermittently, with the most useful data coming from the shipping lanes to the northwest of Cape Town and to the east of Cape Point. In the area to the northwest, waves are from between the south and west (140 to 280 degrees) for 90% of the time while, in the area to the east, there is a broader spread, with waves from the east occurring just 8% of the time.

In more recent years, the site of the Slangkop wave recorder has been moved closer inshore, to a water depth of 70m, in order to avoid downtime from damage by passing ships. It is now possible to monitor wave conditions at Slangkop in real time at http://www.wavenet.csir.co.za The instrumentation has also improved, with the significant wave height being calculated for an interval of 4 hours and wave direction being included since 2000. The results from recent years have confirmed the detail of the earlier wave climatology.

4.2 Big Wave Events from the South-West

The archived wave observations from Slangkop and other wave recorders along the coast of South Africa make it possible to investigate the character of big wave events. Following Van der Borch (2004), a big wave event is defined as one which has a significant wave height exceeding 6.5m for at least 6 hours. This is done to exclude isolated short-term exceedances. Between 1983 and 2003, the records from Slangkop identified 32 such big wave events over the 21 year period, with the actual dates given in Appendix 1.

These 32 big wave events are not distributed uniformly over the 21 year period. They all occur during the winter months of each year, but are clustered together in particular groups of years.

Table 2: Years in which more than one big storm event occurred

1983		**1989**	**1990**	**1991**		**1995**	**1996**	**1997**		**2000**	**2001**	**2002**
3		3	3	2		2	2	2		2	2	4

Table 2 shows that 25 big wave events occurred in 10 particular years, with the other 7 events spread over the remaining 11 years. There appears to be a link between these years with several big wave events, and the years of persistent occurrence of warmer than usual sea surface temperatures in the coastal ocean off south western Africa.

As the second recommendation in this report, an investigation of this possible correlation is suggested as this may provide early warning of likely big storm events in the next winter.

The average significant wave height within these 32 big wave events is 7.72m, with standard deviation 1.01m, which can be compared with the value of the significant wave height at a return period of one year of 7.61m, as given in Table 3.1. The average of the maximum individual wave heights within each big wave event is 12.66m, with a standard deviation of 1.80m, so that the events can certainly be classed as big wave events. The overall maximum individual wave within these 32 big wave events reached 17.09m.

Measured wave direction is available for the nine big wave events from 2000 to 2003. Compared to the directions from the overall wave climatology of Rossouw (1989), there is a more restricted directional spread, with 95% of the records taken within the big wave events being from the south-west between 200 and 260 degrees.

Table 3: Directional wave distribution in percentages for Big Wave Events at Slangkop

		Wave	**Direction in**	**Degrees**		
	200-210	210-220	220-230	230-240	240-250	250-260
Percentage	4%	9%	23%	35%	20%	4%

The period of the swell for these big wave events ranged from 10 seconds to 16 seconds, with a lengthening during the peak of the event.

The daily weather bulletins issued by the South African Weather Service were analysed to identify the nature of the synoptic weather conditions forcing each of the 32 big wave events. The vast majority were associated with the passage of cold fronts (19), cyclo-genesis (7) and even explosive cyclo-genesis (5). The one exception was due to a cut-off low to the south of Cape Town in early September 2001, the event with the individual maximum wave height of 17.09m. Details of the synoptic weather conditions are also to be found in Appendix 1.

4.3 Very Big Wave Events from the South-West

Three of the Big Wave Events investigated in the previous section had significant wave heights which exceeded ten metres, and can be referred to as Very Big Wave Events. Since 2003, there has been yet another Very Big Wave Event, which should be added to the list of four Very Big Wave Events in recent years, deserving of special attention.

The dates of these Very Big Wave Events were as follows:

- **16 May 1984**: Explosive cyclo-genesis of a very deep depression to the south west of Cape Town led to an extreme storm with hurricane force winds and a significant wave height reaching 11 metres. The significant wave height in this storm was sustained at over 8m for over eighteen hours. Considerable damage was incurred by the coastal infrastructure of the south western Cape (Jury et al 1986).

- **5 September 2001**: A cut off low, south west of Cape Town gave rise to strong winds and a significant wave height of over 10 metres. This storm gave rise to the highest individual wave height ever recorded at the Slangkop wave recorder, reaching a massive 17.09 metres. This storm played havoc with shipping, and the bulk carrier Ikan Tanda was grounded on the beach at Scarborough.

- **25 May 2002**: A deepening depression, travelling rapidly to the south of Cape Town was associated with significant wave heights reaching 10 metres.

- **31 August 2008**: A severe storm passing to the south of Cape Town with waves with significant wave heights exceeding 10 metres, at Slangkop, gave rise to very high sea levels along the Atlantic seaboard of the Cape Peninsula. The next day, these high waves entered False Bay and reached relatively unprotected areas of the western shore, where they caused considerable damage to coastal infrastructure. The railway line to Simon's Town was closed for several days, and Jager Walk at Fish Hoek sustained damage of over R1m).

"Very Big Wave Events" with significant wave heights exceeding ten metres should, according to the exceedance diagram in Figure 4, be associated with a return period of 11 years. The occurrence of four Very Big Wave Events over the past 26 years, particularly the occurrence of three such events on the past eight years, suggests that either the frequency or the intensity of Very Big Wave Events is increasing. However, the short record and the tendency of storm events to clump together in the record means that such a conclusion is difficult to confirm.

4.4 Big Wave Events from the South-East

Big wave events from the east will not register at Slangkop, due to the sheltering effect of the Cape Peninsula. Wave recordings are next made at the offshore FA Platform 100km south of Mossel Bay, and wave directions are only available even further east at East London. This means that accurate information on waves entering False Bay from the south east, and usually associated with so-called Black South-Easter meteorological conditions, are hard to find. Recourse has to be made to anecdotal information.

Five big wave events (significant wave height exceeding 6.5 metres and sustained for at least 6 hours) were measured in 2001 and 2002 at East London, and provided directional information. Two of these events were also noted at the FA Platform, but none were noted at Slangkop. Only the first event was associated with waves from the south east, with its peak on 16/17 August 2002, and significant wave heights of 8m. At the FA Platform individual waves were exceeding 14m and this big wave event would have entered False Bay. The records kept at Kalk Bay harbour confirm that rough seas were experienced there on 17 August 2002. Other events of importance at Kalk Bay include 21 April 1996 when two people were swept off the harbour wall and drowned, as well as the storm on 1 September 2008 when considerable damage was caused all along the coast

The records maintained at Kalk Bay Harbour by Marianne Jordaan provide useful anecdotal evidence of the frequency of wave events associated with rough sea conditions and damage at the harbour. Over the past thirty months, the harbour records reveal the following nine instances.

- 13 Feb 2007 Woman knocked into the water.
- 26 June 2007 Wave damage within the harbor.
- 1 Oct 2007 Moorings break.
- 29 April 2008 Rough seas.
- 17 June 2008 Rough seas with more damage.
- 31 August 2008 and 1 Sept 2008. High winds and heavy swell from SW, reaching round to Kalk Bay.
- 11 Nov 2008 Water over harbour wall from heavy SE swell associated with cut-off low.
- 15 to 20 May 2009 bad weather.
- 24 June 2009 SW swell wrapping round. Moorings broken on boats.

It is important to note that these events are spread throughout the year, although there is some influence of winter storms. There are no measurements of actual wave heights at Kalk Bay harbour, though waves reflected off the harbour wall will tend to create standing wave patterns, which will be almost double the height of the incoming waves. These storm waves are responsible for the damage to property in the harbour.

5. Shoaling Effects on Waves, from the Open Ocean to the Surf Break

5.1 Refraction due to Offshore Bathymetry

Refraction effects will reduce the significant wave heights in a straightforward way. The detail requires a comparison between the direction of propagation of the big wave events and the direction of shoaling of the bottom contours as the waves approach the coast. Refraction of an incoming big wave, centred in direction 56.75 degrees at water depth of 70 metres (at the Slangkop buoy), will occur as the wave enters shallow water. If the shoaling direction at the inshore contour is oriented at a greater angle than 56.75 degrees, the incoming wave will gradually bend to the right as it moves into the shallower water. In contrast, if the shoaling direction is oriented at a lesser angle than 56.75 degrees the incoming wave will gradually bend to the left. The extent of the refraction will depend on the amount of shoaling from the deeper water, with more refraction for shallower water, and an eventual alignment of the wave direction with the shoaling direction in the surf zone.

Snell's Law can be used to set up an appropriate Refraction Table at various depths of shallow water and shoaling directions for incident wave direction of 56.25 degrees. At the same time, the proportionate decrease in the incident significant wave height due to the spread of the refracted wave can be noted.

Table 4: Refraction Table for Incident Wave Direction of 56.25 Degrees

Shoaling	-22.5	0	22.5	45	**56.25**	67.5	90	112.5	135
Direction	NNW	N	NNE	NE		ENE	E	ESE	SE
Depth	40m								
Refraction	23.4	39.0	**47.3**	**53.5**	**56.25**	**59.0**	**65.2**	73.6	87.1
Ht Ratio	0.54	0.85	**0.96**	**1**	**1**	**1**	**0.96**	0.85	0.54
Depth	20m								
Refraction	9.1	26.4	**39.8**	**51.0**	**56.25**	**61.5**	**72.7**	86.1	103.4
Ht Ratio	0.48	0.79	**0.93**	**0.99**	**1**	**0.99**	**0.93**	0.79	0.48
Depth	10m								
Refraction	-0.7	18.3	**34.6**	**49.2**	**56.25**	**63.3**	**77.9**	94.2	113.2
Ht Ratio	0.46	0.76	**0.92**	**0.99**	**1**	**0.99**	**0.92**	0.76	0.46

The proportionate decrease in the incident significant wave height in the 40m, 20m and 10m shallow water remains above 0.90 for shoaling directions between NNE (22.5

degrees) and E (90 degrees) where the refraction from the incident direction of 56.25 degrees remains between 34.6 and 77.9 degrees. The correspondence with the spread of the incident wave from 33.75 to 78.75 degrees should be particularly noted. This means that contours with shoaling directions between NNE and E can be considered to be potentially exposed to big storm waves, as there is little reduction in the significant wave height despite the effect of refraction.

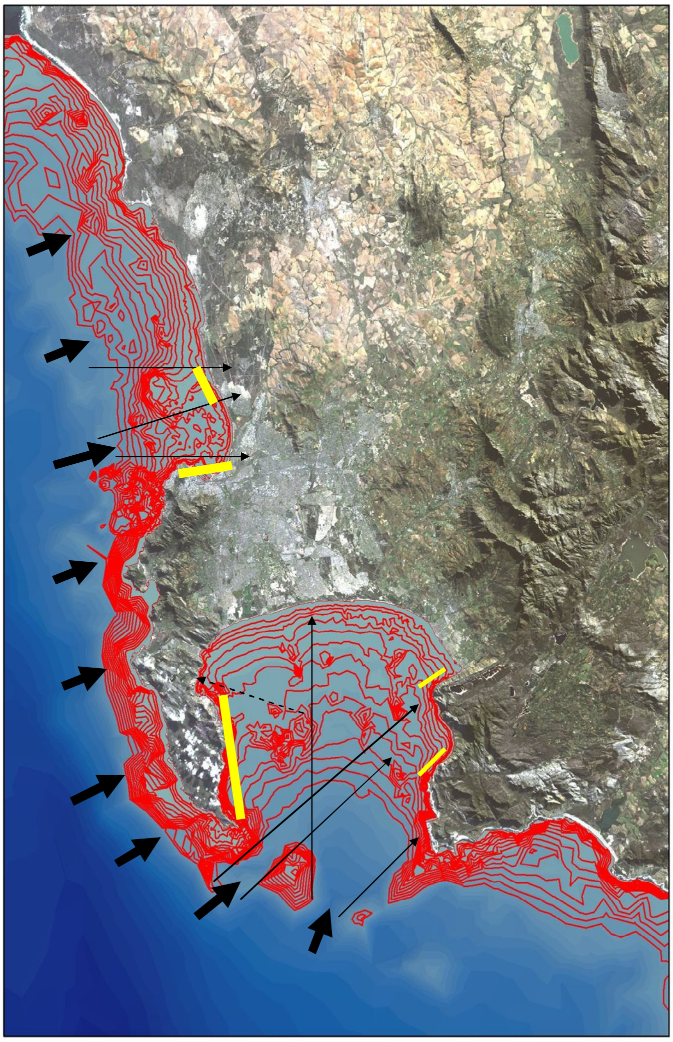

Figure 5. Bathymetry around the Cape Peninsula down to a depth of 70m at 5m intervals.

Much of the Atlantic coast has a shoaling direction between NNE and E, and can be marked as areas potentially exposed to big wave events. The two major exceptions are the coast behind Robben Island, and the sheltered southern end of Table Bay, east of Green Point. There is also a contrast between the gradually sloping bottom contours of

Table Bay, with its sandy beaches, and the steeply sloping contours of the Atlantic coast of the Peninsula, with its cliffs interspersed with mainly pocket beaches. False Bay has gently sloping bottom contours to its northern sandy beaches, but the sides have steeply sloping contours to cliffs and pocket beaches. The entire western shore of False Bay north of Cape Point is potentially sheltered to waves from the south west, whilst everywhere else except for Gordons Bay is potentially exposed.

These coastlines are only potentially exposed because offshore reefs, where they occur, may provide some real protection. By contrast, deep water close inshore can result in a very exposed coast. In the wave shadow, the coastline is only potentially sheltered, because diffraction can transfer significant amounts of wave energy into the shadow zone, particularly if only a small diffraction angle is required. These various possibilities are now explored.

5.2 Bottom Dissipation from Offshore Reefs

Rough bottom topography such as off shore reefs should cause a loss of wave height as wave energy is dissipated through bottom friction. In the north-east corner of False Bay, there is an opportunity to compare observations of break-point significant wave height at a return period of one year, as measured in studies of bathing beaches, with the same significant wave height measured at the Slangkop wave recorder.

Table 5: Significant wave heights with 1 year return periods, at beach break-points on the north-east corner of False Bay and at the Slangkop wave buoy.

	Gordon's Bay	**Strand**	**Macassar**	**Slangkop**
Sign. wave height	1.7m	3.3m	4.9m	7.6m
Ratio to Slangkop	22%	43%	64%	

There is a gradual decrease in significant wave height along the coast from Macassar to Gordon's Bay, due to the effect of refraction and the passage of the waves entering False Bay moving over increasingly greater areas of offshore reef before reaching the coast. The route from the mouth of False Bay to Macassar avoids much of the offshore reef areas, and follows the long gradually shoaling sandy bottom. Even this route sees a reduction to a significant wave height at Macassar of 4.9m over the 7.6m experienced at the Slangkop buoy, for a one year return period. It is worth noting that when high waves coincide with a high tide at Macassar, the beach becomes dangerous for swimming, and erosion of the shore-side dune field is experienced.

5.3 Focusing Effects in False Bay

As waves pass over isolated shallow areas, refraction around the shallow feature can lead to focusing of wave energy and higher waves on the coast. This is a localised effect, which has not been well studied. An exception is the focusing of south-west swell entering False Bay and being focused as the waves pass over the shallow Rocky Bank. Wave energy is then concentrated into the direction that cuts the eastern coast of False Bay at Kogelbaai, a locality associated with fishermen being washed off rocks. It is also possible that the lack of an extensive offshore reef may contribute to the heightened energy on this stretch of coast. A study from Ian Hunter of the South African Weather Service is included as Appendix 3.

5.4 Diffraction into Shadow Zones

The western shore of False Bay from Muizenberg southwards lies in the shadow zone of big wave events travelling through the entrance to False Bay. The waves can be diffracted into the shadow zone and, after refraction by the bathymetry, can reach the coast. The general rule for diffraction is that the greater the angle through which the waves are bent by diffraction, the greater will be the reduction in wave height and wave energy. Thus the big wave events from the south west will have decreasing impact as one moves southward down the coast from Muizenberg/Kalk Bay to Fish Hoek/Simon's Town. Nevertheless the biggest events will still be associated with considerable damage between Muizenberg and Kalk Bay and, even on occasions such as 1 September 2008, at Fish Hoek.

In the same way, there will be considerable interaction between the waves and the bathymetry, as the big storm waves enter Table Bay. Green Point will shelter much of the north facing coast close to the Port of Cape Town, while the breakwaters will protect the Port itself.

6. Coastal vulnerability

So far this study has dealt with wave set-up. That is the waves from the big wave events reaching the outer edge of the surf zone from the open sea. Now attention turns to wave run-up as determined by conditions in the surf zone and on the coast itself. Roughly speaking waves will break when they are close enough to the coast for the water depth to be less than 80% of the wave height. Thus the edge of the surf zone where the waves are 10m in height will be in a water depth of roughly 8m. The resulting width of the surf zone will depend upon the beach slope under the waves from the surf break-point to the shore, on whether the beach is flat or steep. Given that individual waves vary considerably in height, the position of the break-point and the width of the surf zone will also vary considerably. It is the biggest waves that count so that the significant wave height is usually taken as determining the surf break-point and the width of the surf zone. It should also be clear that a tidal range, which approaches 2m at springs, will also have an influence on the character of the surf zone, with possible differences between high tide and low tide.

There will also be differences in the character of the breakers within the surf zone. Details of breaker types and surf zone characteristics can be found in Appendix 4. On relatively flat beaches, plunging breakers can dump much of their energy at the outer break-point itself while, on steep beaches with deep water close to the shore, surging breakers can bring substantial wave energy close to the shore and cause much damage. The very flattest beaches can be associated with spilling breakers that spread their loss of wave energy evenly through the surf zone. Again, the character of the surf zone at each location is not fixed, as there may be differences in breaker types at different states of the tide.

The critical situation is when deep water close inshore allows the wave energy to approach the shore. This may be on a hard coast where cliffs drop deeply into the sea, or where a steep beach is really a dune face, with surging breakers rapidly eroding that dune face. Pocket beaches, a combination of both hard and soft coasts with deep water close to the shore, may be particularly vulnerable.

The experience of the City of Cape Town in repeated maintenance of its protection measures around the coast can be compared with the degree of exposure as revealed in this study.

Exposure, and the associated risk of sea-level rise, is location specific. In this study exposure is disaggregated according to specific location's exposure to wave set-up, wave run-up, the natural predisposition of a location as a function of the coastal geology (hardness and softness of the coastline, where soft coastline is typically less exposed than hard coastline, but particular combinations of hard and soft can lead to heightened risks), and the value or strategic nature of the development in that area.

The table below scores 20 locations that are known to be on the City of Cape Town's list of potentially exposed locations in terms of these four criteria. Applying a binary system, a score of 1 is allocated to those areas that are perceived to be exposed to the specific component of sea-level rise risk, and a score of 0 is given if the location is not exposed to that component. The assessment was conducted using the expert opinion of a group consisting of local oceanographers, coastal conservationists and engineers, all of whom were drawing on a history of experience with the City of Cape town coastline. The assessment not only provides a reasonable measure of the total sea-level rise risk at a given location – and disaggregating risk per location is important – but it also provides important insight into the specific nature of sea-level rise risk at different locations.

Table 6: Components of sea-level rise vulnerability for different locations around the City of Cape Town coastline

	Wave set-up	Wave run-up	Coastal geology. Hard or soft surfaces.	Development risk	Comment
Table Bay: This is an area of gently sloping bottom contours and a sandy coast fringed by low dunes and occasional rocky outcrops. Part of the coast is sheltered by Robben Island. The coast is eroding in the south, and is particularly vulnerable where it is backed by the lagoon of the Diep River.					
Melkbosstrand	1	0	0	1	Exposed to big well, but with some shelter from offshore reefs. Beachfront development and dune removal is problematic.
Blouberg (Bay)	1	0	0	1	Sheltered behind Robben Island, the beach should be an area of sand accretion. However, extensive development has encroached too close to the waterline. Protection is needed.
Tableview beachfront	1	0	0	1	Exposed to big waves, where the Beach Road will become at risk. Protection is needed.
Milnerton beach	1	1	0	1	Exposed to big waves and, at high tide, surging breakers. This is an eroding beach with a diminishing steep dune cordon. Potential major issue if the protection to Otto du Plessis Drive is lost.
Milnerton to harbour	1	0	1	1	Shadow zone, no big waves. Harbour construction has led to gradual erosion and set-back, with ongoing loss of coastal infrastructure. Sea wall needs constant maintenance. Oil pipeline is strategic.

Atlantic Coast: This is a rocky coast with cliffs, offshore reefs and extensive kelp beds. Deep water is found close to the shore, permitting big waves to crash onto the coast so that protection is needed for any infrastructure at sea level.					
Green Point & Sea Point	1	0	1	1	Exposed to big waves, but some shelter from offshore reefs. The coast is on an exposed wave cut platform at some height above the sea, but needs the protection of a strong sea wall requiring continuous maintenance.
Glen Beach	1	0	0	1	A small pocket beach with some protection. High value beach houses are exposed.
Camps Bay	1	1	0	1	This beach is exposed to big waves. Wide beach, but high sea levels can reach the Beach Road.
Bakoven cottages	1	1	1	1	Very exposed to big waves and wave run up, and constantly under threat, as the houses are low down and on a hard rocky surface.
Kommetjie	1	1	0	1	Very exposed as deep water close inshore. Development has taken place in the protective dunefield, reducing its effectiveness.
Witsands	1	1	0	0	Very exposed single building in dynamic dunefield.
False Bay Coast: Western coast is steep but well sheltered from big waves from the southwest. Within False Bay, the bottom contours are gently shoaling to the sandy northern shore. The eastern coast is steep.					
Glencairn	1	0	0	1	Railway line running along a low wave-cut platform. Sheltered in shadow zone, but perhaps the foundations of the railway line in the backing wetland need continual

					maintenance.
Fish Hoek dune section	1	0	0	0	In shadow zone, but backing wetland may lead to vulnerability.
Kalk Bay	0	1	1	1	In shadow zone from southwest, but exposed to focussing from the south-east, so that harbour provides.
Muizenberg corner	1	0	0	1	In the edge of the shadow zone, but protected by a wide and very flat beach with spilling breakers.
Strandfonetin – Baden Powell Drive / Treatment Works / Landfill	1	0	1	1	Not too exposed but the road and the infrastructure are too close to the water's edge.
Monwabisi and Macassar Pavilions	1	1	0	1	Exposed to surging breakers at high tide and during storm events, with erosion of dune field
Strand (entire beach front)	1	0	1	1	Exposed beach with protection from offshore reefs, but infrastructure constructed close to water and poorly planned sea-walls.
Bikini beach	1	0	0	1	In swell shadow, but infrastructure too close to water and needs protection. Beach sand erodes.

In many of these key locations, further study is needed. The character of the surf zone under different conditions of tide and storm will identify the requirements for protection. The occurrence of surging breakers and the erosion of natural dune protection is particularly important. Such local assessments can be made through video monitoring.

7. Incorporation into the GIS

The coastal bathymetry, as illustrated in Figure 5 with contours at 5m intervals down to 70m, has been incorporated into the GIS maintained by the Geomatics Division of the City of Cape Town. This resolution is sufficient for estimates of the effect on significant wave height from refraction, offshore reefs, focusing, and diffraction as the waves move from the open ocean to the surf break. These studies can be summarized as follows.

- The refraction study shows that those parts of the coast with an offshore shoaling direction between NNE and E will be potentially exposed to the big storm waves from the south west. The red areas of the GIS, corresponding to extreme sea levels on the coast of up to LLD+4.5m, will then be potentially appropriate but could be reduced due to other effects.
- The Atlantic coast of the Peninsula itself, because deep water can come close to the coast, will be potentially very exposed to big storm waves from the south west. The orange areas of the GIS, corresponding to extreme sea levels on the coast of up to LLD+6.5m will then be potentially appropriate, but could be reduced due to other effects. Table Bay and the northern and eastern coasts of False Bay would remain as potentially exposed coasts.
- Finally those parts of the coast in the shadow of big storm waves from the south west, such as the lee of Robben Island, the southern coast of Table Bay and the western coast of False Bay, will be potentially sheltered. The blue areas of the GIS, corresponding to extreme sea levels on the coast of only up to LLD+2m, will then be potentially appropriate, but could be increased due to other effects.
- The effect of bottom dissipation as waves travel over shallow water can reduce the significant wave height between the open ocean and the surf break. The study into the north-east corner of False Bay shows that the reduction in significant wave height can exceed 40%, which means that the contribution of wave set-up on exposed coasts can be reduced by a similar amount. This reduction can be used as a first estimate of the bottom dissipation effect on exposed coasts in Table Bay and False Bay. There the extreme sea levels in the red areas should be reduced by 1m to LLD+3.5m.
- Offshore reefs can have an even greater effect, particularly if combined with kelp beds. Areas of coast which are potentially very exposed can actually be sheltered, though this will be a very localized effect.

- Focusing can have the effect of increasing the significant wave energy at points along the coast. The prime example is in False Bay where storm waves from the south west are focused onto the coast at Kogelbaai, countering the dissipation effect in the bay and returning that part of the coast to exposed or even very exposed status. A similar focusing may affect Kalk Bay with big storm waves from the south east.
- Diffraction of wave energy into a wave shadow can mean that a previously sheltered coastline becomes exposed. The amount of exposure to wave set-up can be estimated as thirty percent of the significant wave height at the surf break. It is this additional factor that is responsible for damage to the north western corner of False Bay from big storms from the south west, and for the massive breakwaters protecting Table Bay harbour.

- Finally, if the energy in the big storm waves is undiminished in reaching the coastline at the water's edge, then the potential of an exposed or very exposed coastline can be fully realised. On a hard coast, reflection of the waves off the coast can lead to a doubling of wave height in a greatly enhanced standing wave. On a steep sandy beach, a surging breaker can erode a dune face at an astonishing speed.

Particular areas can be highlighted for special study. The techniques for assessing exposure and protection as the waves move from the open sea to the surf break, as summarized above, can be used in these special studies. If the result is not sufficiently detailed, a period of wave observations at the particular location may be needed to provide the missing detail.

In order to establish the characteristics of the surf zone in the locality of interest, monitoring over various extreme sea levels due to tides and storms through video techniques can provide relevant assessments. The various infrastructure overlays can then be used to investigate the risks of damage.

8. References

Cartwright, A (2008) Global climate change and adaptation – a sea-level rise risk assessment. Phase 3: Sea-level rise risks for the City of Cape Town. Environmental Resource Management Department. LaquaR Consultants.

Jury M.R. *et al* (1986). Meteorological and oceanographic aspects of a winter storm over the south-western Cape Province, South Africa. South African Journal of Science, vol 82, pp. 315-319.

Rossouw, J (1989). Design Waves for the South African Coastline. PhD Thesis, University of Stellenbosch, 140pp.

Van der Borch, E & Van Verwolde (2004). Characteristics of extreme wave events along the South African coast. Applied Marine Science taught Masters Dissertation. University of Cape Town, 124pp.

9. Appendices

Appendix 1: Big Storm Dates and Corresponding Synoptic Situation

Table A1: Big Storm Dates and Corresponding Synoptic Situation

Slangkop		
12-16 May 83		Cold front
18-22 May 83		Cyclogenesis
20-26 Jun 83		Cold front
13-19 May84		Explosive cyclogenesis
28-31 Mar 86		Cold front
27-30 Oct 88		Cold front
28 Mar-3 Apr 89		Cold front
13-16 Jul 89		Cold front
23-27 Aug 89		Cold front
18-22 May 90		Explosive cyclogenesis
10-14 July 90		Cold front
8-12 Aug 90		Cold front
23-27 Jul 91		Cyclogenesis
29 Jul-2 Aug 91		Cold front
20-26 Jun 92		Cold front
18-22 Jun 94		Cold front
5-9 Jul 95		Explosive cyclogenesis
15-19 Jul 95		Cyclogenesis
13-18 Jun 96		Cold front
23-27 Sep 96		Cold front
20-24 Jun 97		Explosive cyclogenesis
25-29 June 97		Explosive cyclogenesis
1-4 Aug 99		Cyclogenesis
13-16 Jul 00	Direction SW	Cold front
16-21 Jul 00	Direction SW	Cyclogenesis
18-21 Aug 01	Direction SW	Cold front
3-7 Sep 01	Direction SW	Cut off low
21-26 May 02	Direction SW	Cyclogenesis
16-20 Jun 02	Direction SW	Cold front
25-30 Jul 02	Direction SW	Cyclogenesis
31 Jul-4 Aug 02	Direction SW	Cold front
17-21 Aug 03	Direction SW	Cold front

Appendix 2: Refraction due to offshore bathymetry

Refraction effects will reduce the significant wave heights in a straightforward way. The detail requires a comparison between the direction of propagation of the big wave events and the direction of shoaling of the bottom contours as the waves approach the coast. These directions will first be converted to the sectors defined by the compass directions.

Table A2: Wave directions during big wave events from 2000-2004 at Slangkop

200-210	210-220	220-230	230-240	240-250	250-260
4	9	23	35	20	4

Compass directions SW and WSW cover angles between 213.75 and 258.75 degrees (45 degree spread with midpoint at 236.25 degrees), which include around 90% of observations of the big wave events. This is chosen as the composite direction from which the big waves come. It will be necessary to turn this around and note that 236.25-180=56.25 degrees is the principal direction in which the big wave events are travelling, with a spread of 33.75 to 78.75 degrees. Thus the big wave events are travelling in compass directions NE and ENE.

A first step is to represent the shelf bathymetry with contour segments, selected from the limited compass direction set, so that the directions may be easily compared with the direction of travel of the big waves. For example the contours off Camps Bay may be N-S, whilst those off the north shore of False Bay may be E-W. The segmented contours are associated with a single shoaling direction. Off Camps Bay, this single shoaling direction is likely to be E, and off the north shore of False Bay, the single shoaling direction is likely to be N.

For refraction of the incoming storm waves, the set of shoaling directions must make an acute angle with the incoming wave. Other shoaling directions are completely sheltered from refraction, though diffraction may bring waves into the sheltered coast, (Eg. the coast of False Bay, south of Muizenberg). With the incoming wave moving in a direction centred at 56.25 degrees, the relevant shoaling directions must lie between -33.75 degrees (or 326.25 degrees) and 146.25 degrees, as given in the following table.

Table A3: Relevant Shoaling Directions as Angles Clockwise from North

Direction	NNW	N	NNE	NE	ENE	E	ESE	SE
Angle	-22.5	0	22.5	45	67.5	90	112.5	135

Refraction of the incoming wave in direction 56.75 degrees at water depth of 70 metres (at the Slangkop buoy) will occur as the wave enters shallow water. If the shoaling direction at the inshore segmented contour is oriented at a greater angle than 56.75

degrees, the incoming wave will gradually bend to the right as it moves into the shallower water. Whilst, if the shoaling direction is oriented at a lesser angle than 56.75 degrees, the incoming wave will gradually bend to the left. The extent of the refraction will depend on the amount of shoaling from the deeper water, with more refraction for shallower water.

Snell's Law can be used to set up Table A.4 as an appropriate Refraction Table at various depths of shallow water and shoaling directions for incident wave direction of 56.25 degrees. At the same time, the proportionate decrease in the incident significant wave height due to the spread of the refracted wave can be noted.

Table A4: Refraction Table for Incident Wave Direction of 56.25 Degrees

Shoaling	-22.5	0	22.5	45	**56.25**	67.5	90	112.5	135
Direction	NNW	N	NNE	NE		ENE	E	ESE	SE
Depth	40m								
Refraction	23.4	39.0	**47.3**	**53.5**	**56.25**	**59.0**	**65.2**	73.6	87.1
Ht Ratio	0.54	0.85	**0.96**	**1**	**1**	**1**	**0.96**	0.85	0.54
Depth	20m								
Refraction	9.1	26.4	**39.8**	**51.0**	**56.25**	**61.5**	**72.7**	86.1	103.4
Ht Ratio	0.48	0.79	**0.93**	**0.99**	**1**	**0.99**	**0.93**	0.79	0.48
Depth	10m								
Refraction	-0.7	18.3	**34.6**	**49.2**	**56.25**	**63.3**	**77.9**	94.2	113.2
Ht Ratio	0.46	0.76	**0.92**	**0.99**	**1**	**0.99**	**0.92**	0.76	0.46

The proportionate decrease in the incident significant wave height in the 40m, 20m and 10m shallow water remains above 0.90 for shoaling directions between NNE (22.5 degrees) and E (90 degrees) where the refraction from the incident direction of 56.25 degrees remains between 34.6 and 77.9 degrees. The correspondence with the spread of the incident wave from 33.75 to 78.75 degrees should be particularly noted. This means that segmented contours corresponding to shoaling directions between NNE and E can be considered to be potentially exposed to big storm waves, as there is little reduction in the significant wave height despite the effect of refraction.

Appendix 3: Weather Systems and Enhanced Wave Conditions in False Bay – 12 November 2008

Last Wednesday 12 November 2008 heavy seas once again crashed over the breakwater into the Kalk Bay fishing harbour threatening the adjacent restaurants. Fortunately the wave conditions did not reach the extremes of 1 September when considerable damage was incurred – not just in Kalk Bay but all along the coast from Table Bay to East London.

Earlier this year on 17 June heavy seas resulted in some of the concrete fish-cleaning tables inside the harbour being smashed. Thus enhanced wave conditions in this area are by no means rare. They also occur along other sections of the False Bay coastline - between Steenbras River Mouth and Cape Hangklip numerous crosses mark the spots where rock anglers have been caught unawares.

Divers and small boats have similarly fallen foul of these sudden, short-lived events.

Figure A1: A cross located just to the west of Steenbras River Mouth marks one of many spots where rogue waves have washed fisherman into the sea. The swell direction at the time of these tragedies is invariably SW'ly – with wave focussing taking place as a result of bathymetrical features

Heavy SE'ly swell entering False Bay – cut-off low/ blocking high combination
In 1965 a naval cutter (ship's boat with sailing gear) was becalmed off Kalk Bay when a sudden, quick succession of steep high waves capsized the vessel, resulting in the loss of 7 of the 11 crew members. In this case the swell direction was SE'ly. This latest event (12 November 2008) was also a case of a heavy SE'ly swell entering the Bay – and being focussed onto the Kalk Bay area. These events are almost always associated with a cut-off low event (COL). See Figure A2, the sea level pressure analysis on the morning of 12 November.

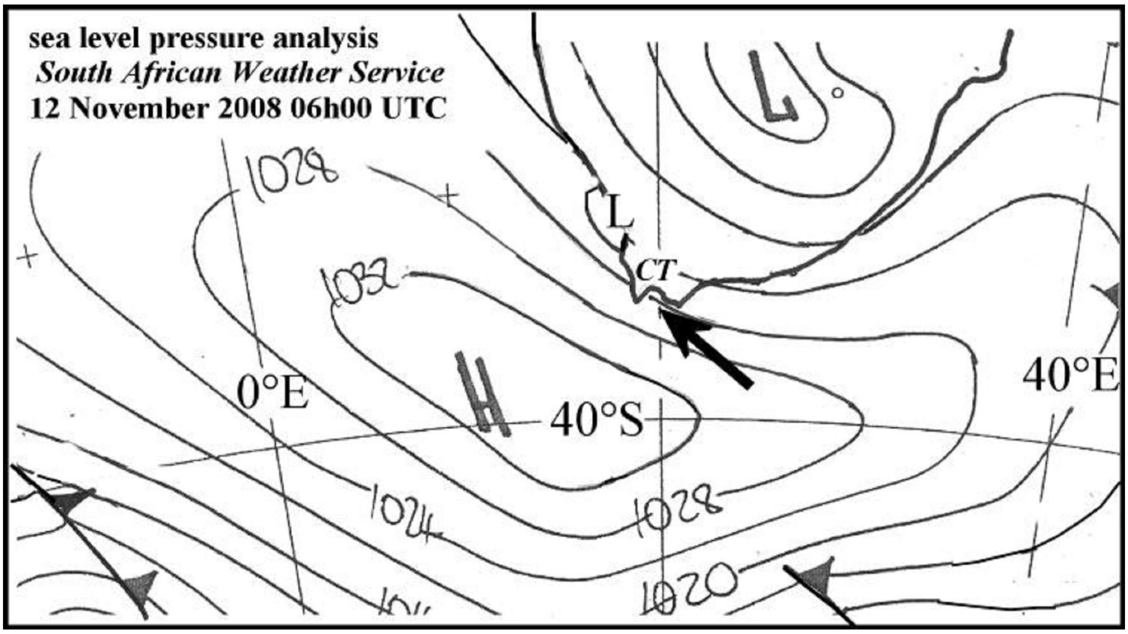

Figure A1: SAWS sea level pressure analysis for 06h00 on 12 November 2008. Note that the wind is angled across the isobars due to friction and pressure gradients increasing rapidly with time

The term 'cut-off' actually refers to the upper air circulation but this sea level analysis shows the typical pattern - a tight SE'ly fetch zone (arrowed) squeezed in between a COL / Blocking High combination. Compared with the normal Cape SE'er the high is generally further south, the low is deep (not your normal shallow, coastal low) – and sometimes located offshore. Both systems are *semi-stationary*, thus increasing the wave generation 'duration' factor.

There is a longer-than-normal fetch zone and all of this combines to build up an unusually heavy SE'ly swell. The swell period is relatively short, but Whittle Rock is shallow – refraction and focussing still come into play. The blue arrows in Figure 4 apply, with thickness representing wave energy.

Note that the sea state on the Western Cape's *west* coast remains relatively calm in these (deep) SE'ly conditions – the wind being offshore and there thus being a very limited fetch.

Heavy SW'ly swell – intense mid-latitude trough

The extreme wave conditions of 31 August and 1 September were associated with a deep mid-latitude trough moving fairly rapidly eastwards (cf stationarity of COL/ Blocking High combination).

Rocky Bank (which rises to 22m, 5nm southeast of Cape Point) has been identified by means of wave refraction diagrams as the bathymetric feature responsible for focusing a heavy SW'ly swell onto the coast between Steenbras River Mouth and Rooiels. However, in the case of a particularly long period SW'ly swell the effect of the Bank is to refract the wave energy even more – and focus it onto the Kalk Bay area Thus abnormal wave conditions in Kalk Bay can be associated with both heavy SW'ly and heavy SE'ly swell conditions.

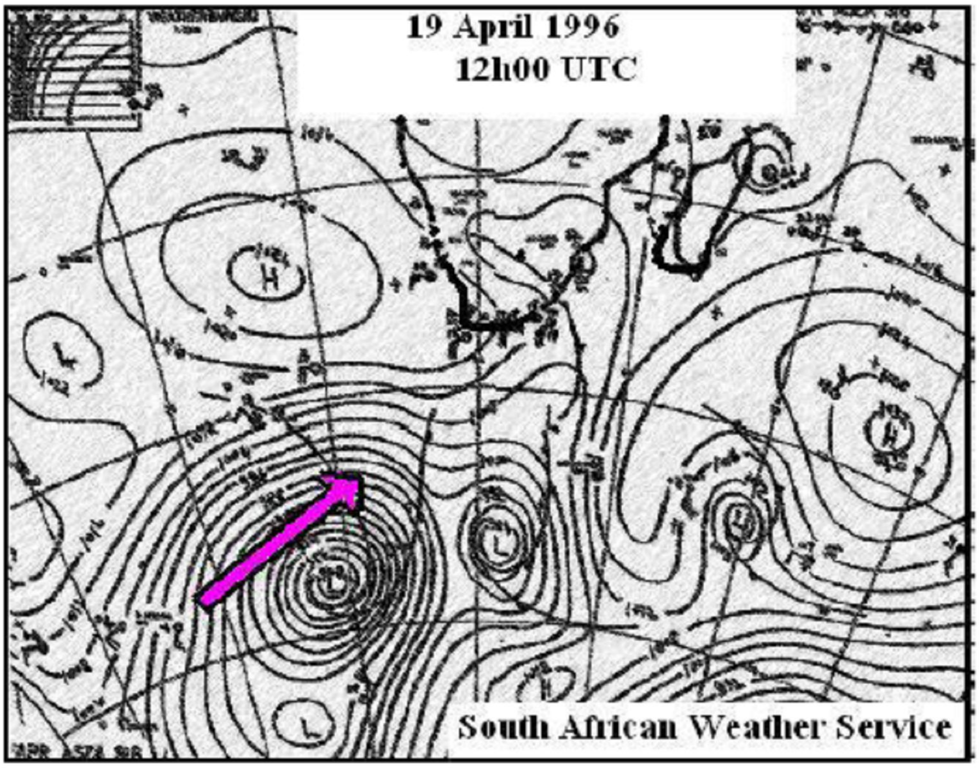

Figure A2: Sea level pressure analysis for 12h00 UTC on 19 April 1996. The arrow indicates the tight SW'ly fetch zone in which winds upwards of 60 kts were probably present. In the associated vortex central pressure dropped below 950 hPa.

Figure A2 shows the sea level pressure analysis associated with a long-period ***SW'ly swell*** that resulted in the deaths of 2 people, swept off the Kalk Bay breakwater on 21 April 1996 (cf red arrows in fig A3). Note that the date of the analysis is 19 April – 2 days before the swell arrived in False Bay. As the SW'ly swell travelled the ~ 2000 km wave energy would have been shifting into the longer periods (i.e. longer wavelengths). Even at 22m depth Rocky Bank had a marked effect, turning and focussing the swell into the northwestern corner of False Bay.

During the period 30 August to 2 September 2008, when many millions of rands damage was done to coastal infrastructure, the dominant wave-generating synoptic scale weather system was again a relatively fast-moving, intense mid-latitude trough. The near-record (deep sea) wave heights may well have been related to the propagation speed of the front and the extensive SW'ly fetch zone it dragged behind it.

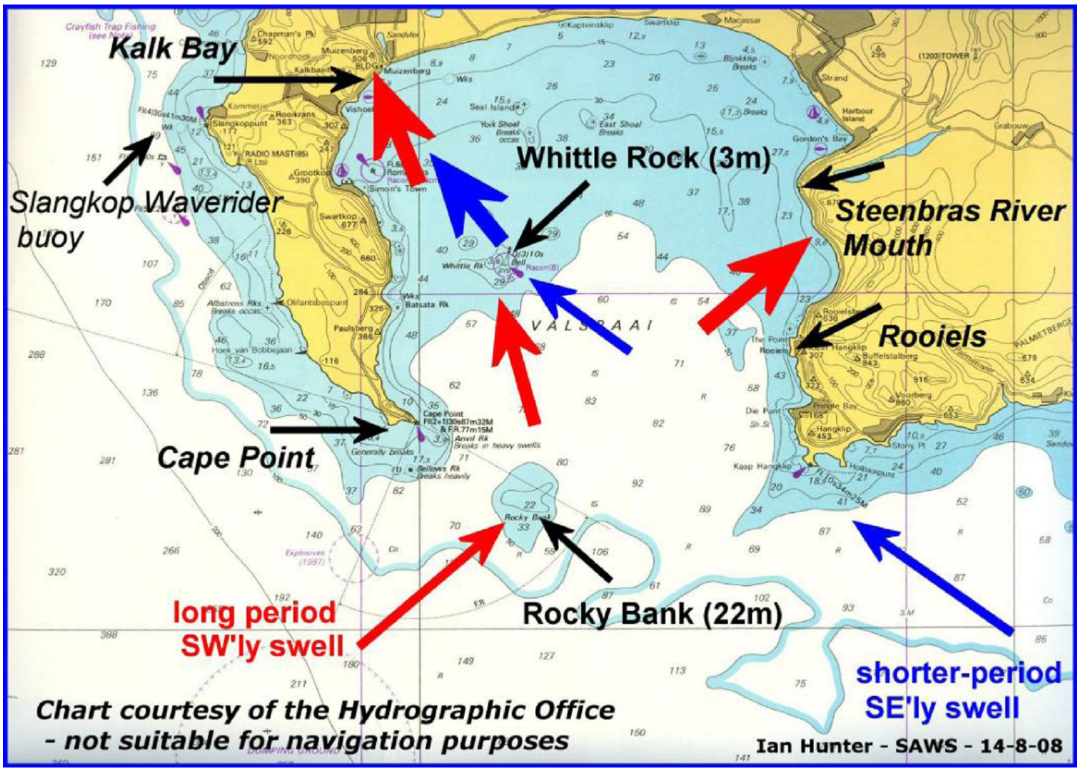

Figure A3: Refraction and focusing in False Bay – SW'ly (red) vs SE'ly (blue) swell conditions

Figure A3 has been annotated so as to indicate the relevant swell directions and some of the wave focusing areas associated with them. In the open ocean south of Cape Town a heavy SW'LY swell is far more common than one from the southeast, but in years when numerous cut-off lows are experienced over the Western Cape (e.g. 2008), Kalk Bay may suffer almost equally under both conditions.

Appendix 4: Wave type and energy

Characterisation of breaker types can be established through the surf scaling parameter E

$E = (2*PI^2*H_b) / (g*T^2*tan^2(beta))$

H_b is breakpoint wave height
T is wave period
Beta is surf zone bottom slope

E is also related to the Iribarren Number given by the square of the bottom slope divided by the wave steepness.

Spilling breakers	$20<E$	dissipates energy evenly through entire surf zone.
Plunging breakers	$2.5<E<20$	dumps energy at the break point.
Surging breakers	$E<2.5$	carries energy to beach to be reflected.

Flat beaches, such as Muizenberg, are associated with spilling breakers and are referred to as dissipative beaches. Steep beaches, where deep water comes close to the coast, are associated with surging breakers and are referred to as reflective beaches. Estimates of inshore bottom slope are needed for the calculation of surf scaling parameter, particularly on exposed beaches. The bathymetric charts may not give enough information close to shore, but video studies can help.

Estimates of wave period can be obtained from the observations of the big storm waves at the Slangkop buoy. An estimate of the break point wave height can be obtained from the deep(er) water wave height at the Slangkop buoy by using Komar's approximation.
$H_b = 0.39\ g^{0.2} (T\ H_0^2)^{0.4}$ T period, H_b break point height, H_0 buoy height.

Appendix 5: Terms of Reference for Phase 5 study

The primary objective of this study is to improve understanding of the extent and manner in which City of Cape Town's coastline is likely to be impacted by sea level rise. It is propose to achieve this by adding the influence of local factors such as offshore bathymetry, storm direction and coastal geography to the sea level rise model developed in Phases 1-4, and by including an understanding of how the various influences on sea-level rise interact with each other at a specific locations and over time.
Realising this primary objective rests on the incorporation of data pertaining to:

- Knowledge of the offshore wave climatology.

- The detail of the coastal bathymetry and its influence on wave run up.

Both these data are limited by the resolution of available observations. This appears to be recognised in the Terms of Reference by the restriction of the wave directions to the coarse compass directions NW, W, SW, S and SE. The course resolution will place constraints on the type of model and the accuracy of the results that can be expected from such models. Nevertheless, it should be possible in this Phase 5 to achieve the outcomes asked for in the Terms of Reference, namely:

- Develop a finer scaled and more accurate approach to the existing GIS model by identifying areas at risk due to a uniquely varying shoreline, bathymetry and coastal geography;
- Apply five storm direction scenario's to the City's coastline (NW, W, SW, S and SE);
- Identify key risk areas for each storm direction scenario based on swell direction, bathymetry, shoreline, swell shadows and coastal geography, and
- Improve the level of accuracy in the predictions for sea level rise events

Once these key risk areas have been identified, further observation programmes at a greater resolution can be contemplated, with a view to obtaining more predictive capability from the use of sophisticated inshore wave models.

The approach proposed for this study is to add to the factors in the existing GIS to enable impact variability along the coast to be assessed and predictability improved. The following aspects will be investigated:

- Swell dynamics i.e. characteristics of swell direction;
- Correlations that may exist between the various swell characteristics i.e. average wave height and wave length may be associated to a particular swell direction, time of year, wind direction, weather pattern etc;
- Coastal areas that will receive specific swell head-on, and those that will be sheltered from swell based on the five different storm direction scenarios;
- Critical coastal bathymetry. Shallow offshore banks will play a significant role in reducing swell energy reaching the coast whereas deeper near-shore bathymetry will result in increased wave energy reaching the coast;
- The effect of coastal geology and topography on hinterland vulnerability (sandy shore vs rocky shore)
- The direction and dynamics of longshore drift;
- The presence, state and influence of other natural barriers i.e. kelp forests in terms of reducing the impacts of storm swell and in which areas;
- The physical composition of the beach: A combination of rocks and sand tends to be more susceptible to erosion, and
- Vulnerable areas as a result of human development and activity.

Appendices References

Aarninkhof, S.G.J. (2003). *Nearshore bathymetry derived from video imagery*. PhD. Thesis, Delft University of Technology, 175 pp.

Holland, K.T. and Holman, R.A. (1993). The statistical distribution of swash maxima on natural beaches. *Journal of Geophysical Research*, 98, pp. 10271-10278.

Plant, N.G. and R.A. Holman. (1997) Intertidal beach profile estimation using video images. Marine Geology 140(1-2): 1-24.

Global Climate Change and Adaptation: City of Cape Town sea-level rise risk assessment.

Phase 5: Sea-level rise vulnerability assessment and adaptation options

Anton Cartwright

anton@econologic.co.za

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econologic
economics for people & planet

Contents

1. Introduction

People have been adapting to variability in the City of Cape Town's coastal zone for as long as they have lived there, but anthropogenic climate change presents novel challenges and is exposing the imprudence of some of the coastal development that has taken place.

Phase 3 of this study (Brundrit et al., 2008) estimated that 25 km^2 of land interior to the City of Cape Town's 307 kilometre coastline is currently exposed to high sea-events 2.5 metres above land levelling datum (LLD), caused by a coinciding extreme high tide and storm surge. There is R5 billion worth of infrastructure and property within Cape Town's 2.5 metre contour, and although no single event would affect all of this at the same time, it is clear that the City is exposed to sea-level rise risks. Seas 2.5 metres above LLD are not common, but as storms become more frequent and the mean sea-level platform on which these storms and tides manifest is raised, this could change.

In the initial component of this Phase 5, Brundrit advanced the work undertaken in Phases 1-4 by identifying those areas of the City of Cape Town's coastline that are particularly vulnerable to this "current worst case" scenario. In mapping this vulnerability, Brundrit applied four physical attributes – (1) wave set-up as influenced by bathymetry, swell direction, swell conversion and shoaling (2) wave run-up as influenced by the topography of the coast and bathymetry (3) geological predisposition of the coastline as influenced by the hardness or softness of the coastline and (4) the extent and nature of coastal development – to the altitude parameter that was used exclusively in Phases 1-4:

i. **Wave set-up** is a function of wind, swell direction and the extent to which waves are refracted by the coastal topography; refraction reduces wave energy. Brundrit shows that most significant sea-surges off the Cape Town coast approach from the south-west (200 - 260°). Coastlines that front directly to these seas are the most vulnerable. Offshore reefs, islands and wave refraction typically reduce exposure to wave set-up. Thirty two "wave set-up events" – waves off the coast of over 6.5 metres lasting longer than 6 hours – were recorded off the City of Cape Town's Atlantic coastline between 1981 and 2003. Brundrit notes a correlation between these events and warmer sea surface water south west of Cape Town, and suggests a better understanding of the relationship between atmospheric temperature, sea temperatures in this region and large waves is important.

ii. **Wave run-up** is defined by the extent to which waves advance inland once they have broken, and the energy with which they advance. Wave run-up is reduced by bottom friction and accordingly coastlines with gradual gradients, coarse shallow sea-surface bottoms (such as those with reefs) and beaches protected by kelp tend to be less prone to wave run-up. Conversely where deep water is found close to the coastline, wave run-up can cause aggressive coastal erosion and damage. Wave run-up can be influenced by "wave focusing" – the convergence of waves from different angles, as is the case at Kogelbaai in False Bay.

iii. **Coastal geology** determines the hardness or softness of the coastline. The hardness (rockiness or sea-wall) or softness (sand or vegetation) of a coastline in turn determines its "natural" ability to withstand or recover from sea-level rise risks and its predisposition to storm damage. As a rule of thumb soft coastlines are more able to absorb wave energy and withstand sea-level rise impacts than hard coastlines. Well engineered coastlines can, of course, reduce sea-level rise risk but the danger is that poorly engineered coastlines either transfer or concentrate wave energy onto a single point or are over-topped by high seas. The engineering of coastlines usually takes place at the expense of natural buffers, and where (hard) engineered defences are breached the coast is particularly vulnerable. In this way some of the most vulnerable coastlines are those that involve a combination of hard and soft surfaces. Roads built on beaches and sea-walls in conjunction with sand dunes, are particularly vulnerable.

iv. **Value and strategic nature of the development.** From the City of Cape Town's perspective, coastal vulnerability is a function of the assets (natural or constructed) that the coastline contains. This is true in two ways. Firstly the assets, whether houses, roads or wetlands, are a part of the coastline's composition and determine the damage that a given storm event can cause. Secondly, the value (both economic and strategic) that the coastline contains determines the extent of what is at risk from sea-level rise. If a section of coastline containing a major access road to the City is at risk from sea-level rise, this is probably a greater priority than a remote section of coastline at which only sand and rocks are exposed. Similarly, if a wetland that prevents flooding and provides a habitat for rare species is at risk, this is arguably a greater priority than a section of coastline containing only common vegetation and no specific habitats. The nature and extent of development provides further important insight into who is liable for sea-level rise damage and the cost of adaptation measures. Private infrastructure - houses for example - that have been constructed naively close to the sea may present the potential for significant loss of value (especially where the houses are high value), but may not be considered the City's responsibility. Public infrastructure or infrastructure that if damaged will have a significant impact on the public may in contrast be considered a high priority for the City.

By screening for exposure to wave set-up and wave run-up Brundrit was able to identify those areas that were respectively:

- "Sheltered": Currently exposed to events 2 metres above land levelling datum, and most sensitive to changes in mean sea-level.
- "Exposed": Currently vulnerable to some wave run-up and set-up capable of causing events 4.5 metres above land levelling datum. These areas are exposed to changes in both mean sea-level and the changing nature of storms and sea-surges.

- “Highly exposed”: Currently prone to events of 6.5 metres and vulnerable to both wave set-up and run-up. For these areas the changing nature and frequency of storms is critical, and the rising mean sea-level is important.

Figure 1 shows (in yellow) “sheltered” coastlines as well as the extent of the exposure of Cape Town’s Atlantic coast to storm action. Local experts drew on their knowledge of past events to “ground truth” this work and a collective effort identified “hot spots” around the City of Cape Town’s coastline. Hot spot locations are particularly vulnerable to coastal damage. In taking this step it was necessary to add the distribution of valuable infrastructure and human settlement to Brundrit’s physical and climate oriented map.

A key realisation to come from Brundrit’s work is that different coastal settlements are vulnerable to different combinations of change in mean sea-level, swell direction and size and wave run-up.

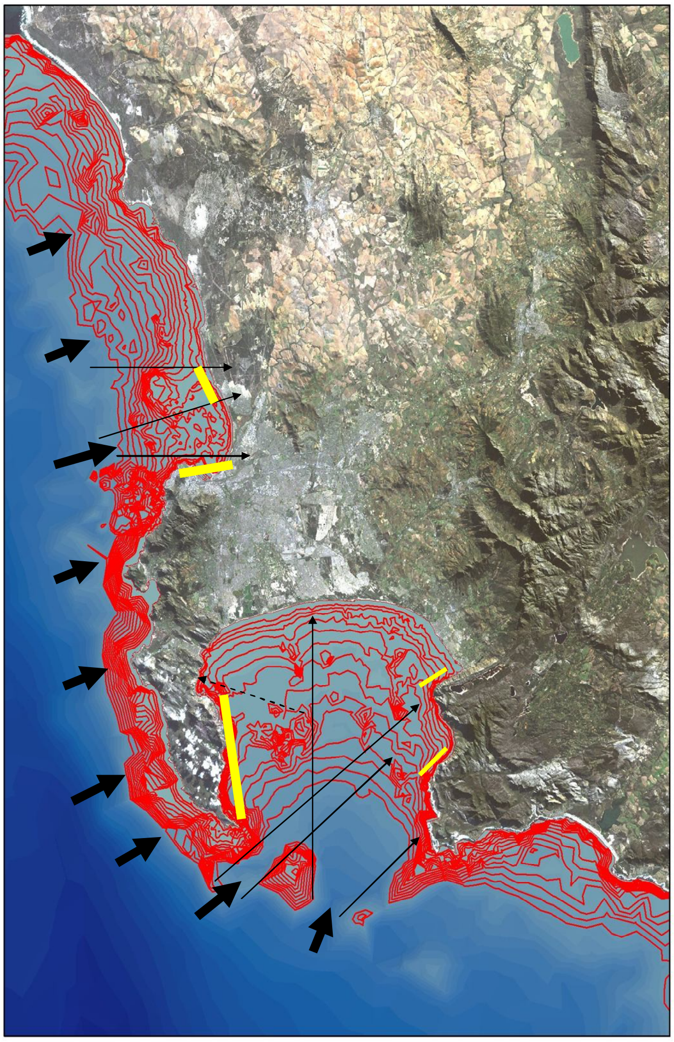

Figure 1: Sheltered and vulnerable regions based on wave set-up and wave run-up. (Source: Brundrit, 2009).

The hotspots were then subjected to an additional screen that involved including hardness and softness of the coastline and the extent and nature of coastal development to the parameter of wave set-up and run-up. The four parameters were used to provide a screen that differentiated the extent and reason for vulnerability at the respective “hot-spot” locations (see Section 3).

2. New risks to Cape Town’s coastal zone

In most instances the list of vulnerable “hot spot” locations confirms what people in the City of Cape Town already know. In some instances efforts are already underway to protect these areas. This might suggest that approaches used to cope with sea-level rise events in the past, provided they are maintained, will serve Cape Town’s residents well in the future. After all many of the topographical and geological parameters applied in identifying exposure to wave run-up and wave set-up are not changing over time frames that are significant to planners.

New concerns over coastal vulnerability in Cape Town are based both on (1) the increasing value of infrastructure, property and human life found proximal to the coastline and (2) changes in mean sea-level (land levelling datum) and the frequency and intensity of storms. There is further concern over the lack of a coherent approach in dealing with arising threats, and the reliance on ad-hoc and reactive responses. The basis for these concerns is expounded below:

2.1 Mean sea-level:

Measures of mean sea-level are complicated because the sea is neither level nor rising at a uniform rate around the world. The Intergovernmental Panel on Climate Change’s (IPCC) Fourth Assessment Report (2007) cited an average change in sea-levels of 0.17 (0.12-1.22) metres over the 20th Century and projected an upper-limit increase of 0.59 (0.18-0.59) metres by 2100. For all but the world’s low lying islands these changes are within the bounds of previous high tides and severe storm surges. However Krabill et al. (2004), Velicogna and Wahr (2006), Rignot and Kanagaratnam (2006), Hansen[1] (2007) and Tol et al. (2008) have questioned the IPCC projections. Much of their work is focussed on the potential for non-linear, rapid melting of the Greenland and West Antarctic Ice Sheets. Such events would result in sea-level rise an order of magnitude greater than those projected by the IPCC. The likelihood of larger and more rapid sea-level increases appears to be supported by a range of anecdotal observations recorded in UNEP’s 2008/9 Year Book[2]. Collectively this evidence suggests that atmospheric temperature increases are merely the catalyst for complex ice sheet collapse processes that, once underway, become driven by more than temperature. UNEP (2009) notes:

[1]Jim Hansen is head of NASA's Goddard Institute for Space Studies.

[2] The Year Book was released on 10 March 2009 in Nairobi.

- In 2008, for the second year in a row, there was an ice-free channel in the Northwest Passage through the islands of northern Canada. 2008 also witnessed the opening of the Northern Sea Route along the Arctic Siberian coast. The two passages have probably not been open simultaneously since before the last ice age some 100,000 years ago.

- The Greenland Ice Sheet, which could raise sea levels by six metres if it melted away, is currently losing more than 100 cubic kilometres a year. This is faster than can be explained by natural melting.

- Losses from the West Antarctic Ice Sheet increased by 60 per cent between 1996 and 2006, while losses from the Antarctic Peninsula increased by 140 per cent over the same period.

There is, then, some uncertainty over the extent and rate of climate change induced sea-level rise. What is clear is that globally sea-levels are rising, the rate of rise is increasing and relatively small increases in mean sea-level have disproportionately large impacts on the damage that storms cause to the coastal zone.

Measurements taken at Port Nolloth between 1962 and 1987 (Brundrit, 1995) and Durban between 1970 and 2003 (Mather 2007) show average rises of 1.2±0.4 mm per annum and a 2.7±0.05 mm rise per annum, respectively. Based on this Brundrit concludes that mean sea-level in Cape Town is probably rising in line with the global mean, and is currently 0.2 metres above the average for the past 100,000 years. In the context of a tidal flux for the same region of 2 metres and storms that produce 2 metre waves, this may not sound particularly significant, but (as shown in Figure 2) a small increase in mean sea-level reduces the frequency with which a 1.7 metre sea-level rise event occurs from one in 700 years to one in 40 years. Sea-level rises lag atmospheric warming due to the processes that govern thermal expansion of the oceans. The mean sea-level rises that are already inevitable, based on existing atmospheric warming, will see dramatic coastal events becoming more common along the Cape Town coastline. Not only would this reduce the recovery time between events, but it would also allow the sea to impact upon sections of the coastline that have little resilience to such impacts.

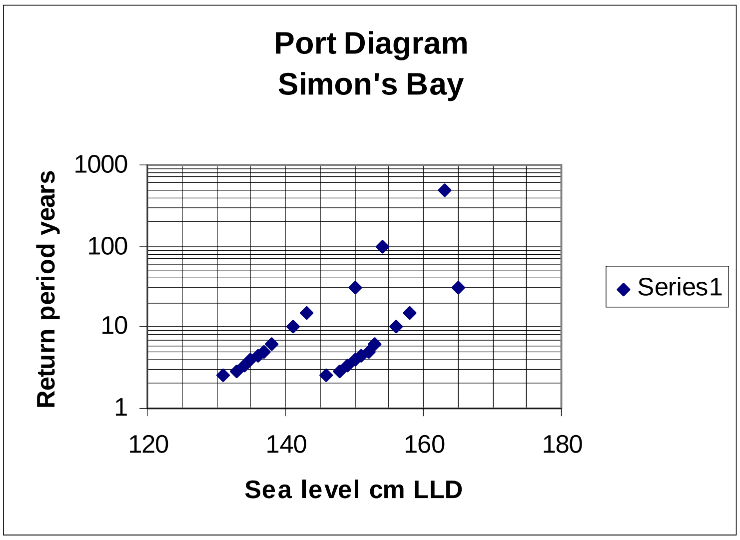

Figure 2: Return period of extreme sea levels expected in sheltered areas at the present time, and after sea-level rise of 20cm. The figure shows that return times of extreme sea-level events are a log function of land levelling datum; small changes in land levelling datum have a disproportionate impact on the frequency of extreme events.

2.2 Coastal storms:

The risks caused by changes in mean sea-level are compounded by the anticipated impacts of climate change on the intensity and frequency of storms. SwissRe (2009) projects a small decrease in the number of extra-tropical cyclones, but a 15-20 per cent increase in the occurrence of severe extra-tropical cyclones, particularly in the southern hemisphere. SwissRe's conclusion is supported by Lambert and Fyfe (2006) and broadly consistent with the findings of Bengtsson et al. (2006), who cite a "poleward shift" of mid-latitude storm tracks.

Definitive local studies of the relationship between atmospheric temperature and storms are still emerging, but the available downscaled evidence is consistent with the international trend (Tadross[3] pers. comm.). A more specific hypothesis (Brundrit, 2008) proposes that the Atlantic coastline is being exposed to increasing frequency and intensity of south-west storms – the storms that have accounted for all of the major sea-level rise events in the past three decades (Schumann and Brink, 1990) - but definitive support for this is not yet available. MacDeevit and Hewitson (2007) projected a doubling of the incidents of extreme winds (7.6 m/s) in the Western Cape by 2081-2100, and it is known that increases in wind speed cause a disproportionate increase in wave height. Brundrit (2009) shows that "very big wave events" have occurred every 11 years on average over the past two hundred years, but notes four such events in Cape Town in the past twenty six years.

[3] Mark Tadross is a climatologist at the University of Cape Town's Climate Systems Analysis Group.

In short there is the distinct possibility that either or both the frequency and intensity of the south west storms that cause most of the coastal damage in the City of Cape Town, could be exacerbated by climate change and monitoring this change will be particularly crucial for those locations exposed to south west wave set-up and wave run-up.

2.3 Socio-economic development:

Cape Town's physical and climatological predisposition to coastal vulnerability is aggravated by institutional and socio-economic developments. Much of the peninsula's transport infrastructure (most notably the False Bay Railway line) is built on a wave-cut platform created 125,000 years ago by sea-levels 4-6 metres higher than present. At the same time coastal property has become increasingly sought-after and the value of coastal development has escalated. The country's White Paper on Sustainable Coastal Management (2000) describes the coast as a "national asset" and encourages "sustainable economic use" of this asset without compromising its "ecological integrity". In the past, however, land reclamation, the removal of coastal dunes, the stabilisation of sand that has historically replenished beaches, the development of estuaries (Turpie, 2004) and sand mining have collectively reduced many of the coast's natural buffers, exposing sections of the coastline to damage from increasingly variable and rising seas.

Cape Town's coastal development has altered the "hardness" and "softness" of coastline, which in turn influences the impacts that given waves, tides and changes to mean sea-level have on the coastline. As a rough rule softer coastlines – that is coastlines with a combination of vegetation, kelp, reefs, sand and natural contours – absorb wave energy better than hard coastlines containing rocks or walls. Soft coastlines can, however, be more damaged by storms and where the natural forms of replenishment and rehabilitation have been curtailed, can be easily perturbed and permanently damaged.

2.4 Coastal governance:

Institutionally the governance of coastal zones in Cape Town is patchy. Most beaches are officially "crown land" and under the jurisdiction of national government, but the land immediately adjacent to beaches belongs to an array of national government departments, agencies and local authorities. The public company Portnet is responsible for the Cape Town harbour, but The City of Cape Town is obliged to extend and maintain services to individuals and companies that own coastal land and have received planning permission. Unfortunately the authorities granting planning permission are not always the same authorities that are cognisant of sea-level rise risks.

The situation is compounded by the historical exclusion of much of Cape Town's population from coastal amenities and coastal properties. Under apartheid, black and coloured people were not able to share in the development of coastal property that proved lucrative for white Capetonians, and were not permitted to share public amenities such as beaches and swimming pools. Politically motivated restrictions to coastal access in the past make current attempts to prevent coastal development sensitive.

3. Assessing sea-level rise risk at Cape Town's coastal locations

Table 1: Components of sea-level rise vulnerability for different exposed locations around the City of Cape Town coastline

	Wave set-up	Wave run-up	Coastal geology. Hard or soft surfaces.	Risk to infra-structure and ecological assets	Comment
Table Bay: This is an area of gently sloping bottom contours and a sandy coast fringed by low dunes and occasional rocky outcrops. Part of the coast is sheltered by Robben Island. The coast is eroding in the south, and is particularly vulnerable where it is backed by the lagoon of the Diep River.					
Melkbosstrand	1	0	0	1	Exposed to big well, but with some shelter from offshore reefs. Beachfront development and dune removal is problematic.
Blouberg (Bay)	1	0	0	1	Sheltered behind Robben Island, the beach should be an area of sand accretion. However, extensive development has encroached too close to the waterline. Protection is needed.
Tableview beachfront	1	0	0	1	Exposed to big waves, where the Beach Road will become at risk. Protection is needed.
Milnerton beach	1	1	0	1	Exposed to big waves and, at high tide, surging breakers. This is an eroding beach

					with a diminishing steep dune cordon. Potential major issue if the protection to Otto du Plessis Drive is lost.
Milnerton to harbour	1	0	1	1	Shadow zone, no big waves. Harbour construction has led to gradual erosion and set-back, with ongoing loss of coastal infrastructure. Sea wall needs constant maintenance. Oil pipeline is strategic.
Atlantic Coast: This is a rocky coast with cliffs, offshore reefs and extensive kelp beds. Deep water is found close to the shore, permitting big waves to crash onto the coast so that protection is needed for any infrastructure at sea level.					
Green Point & Sea Point	1	0	1	1	Exposed to big waves, but some shelter from offshore reefs. The coast is on an exposed wave cut platform at some height above the sea, but needs the protection of a strong sea wall requiring continuous maintenance.
Glen Beach	1	0	0	1	A small pocket beach with some protection. High value beach houses are exposed.
Camps Bay	1	1	0	1	This beach is exposed to big waves. Wide beach, but high sea levels can reach the Beach Road.
Bakoven cottages	1	1	1	1	Very exposed to big waves and wave run up, and constantly under threat, as the houses are low down and on a hard rocky surface.
Kommetjie	1	1	0	1	Very exposed as deep water close inshore.

					Development has taken place in the protective dunefield, reducing its effectiveness.
Witsands	1	1	0	0	Very exposed single building in dynamic dunefield.
False Bay Coast: Western coast is steep but well sheltered from big waves from the southwest. Within False Bay, the bottom contours are gently shoaling to the sandy northern shore. The eastern coast is steep.					
Glencairn	1	0	0	1	Railway line running along a low wave-cut platform. Sheltered in shadow zone, but perhaps the foundations of the railway line in the backing wetland need continual maintenance.
Fish Hoek dune section	1	0	0	0	In shadow zone, but backing wetland may lead to vulnerability.
Kalk Bay	0	1	1	1	In shadow zone from southwest, but exposed to focussing from the south-east, so that harbour provides.
Muizenberg corner	1	0	0	1	In the edge of the shadow zone, but protected by a wide and very flat beach with spilling breakers.
Strandfonetin – Baden Powell Drive / Treatment Works /	1	0	1	1	Not too exposed but the road and the infrastructure are too close to the water's edge.

Landfill.					
Monwabisi and Macassar Pavilions.	1	1	0	1	Exposed to surging breakers at high tide and during storm events, with erosion of dune field.
Strand (entire beach front).	1	0	1	1	Exposed beach with protection from offshore reefs, but infrastructure constructed close to water and poorly planned sea-walls.
Bikini beach	1	0	0	1	In swell shadow, but infrastructure too close to water and needs protection. Beach sand erodes.

The risk analysis in Table 1 provides a number of important insights. Most obvious is that sea-level rise risk – a term that is applied at various scales and in an increasing number of contexts - is location specific and the result of different causes. The same sea-level rise event can affect places located quite close together, in very different ways due to the topography of the location, the orientation of the coastline relative to swell direction, the hardness or softness of the coast and the extent and type of coastal development. Understanding the particular combination of wave run-up, wave set-up, coastal erosion, change in still water level and imprudently located construction that affects a given location, is essential in correctly monitoring the changing nature of this risk under climate change and in the formulation of effective adaptation measures.

Secondly unless the respective components of sea-level rise are understood, it is very difficult to manage the trade-offs between development and coastal protection in a coherent manner. The most appropriate responses to wave-set up risks and wave run-up risks will, for example, differ. Equally the construction of hard infrastructure at a location that is naturally “soft”, but prone to wave set-up (such as Llandudno beach), is unlikely to be effective and likely to cause unforeseen consequences. Similarly the use of soft measures – such as sand replenishment – at hard locations that experience exposure to wave set-up (such as Bakoven) is unlikely to prove effective.

A further insight to emerge clearly from the analysis is that most sea-level rise risks have their origins in ill-advised coastal development. Climate change induced sea-level rise is exposing poor coastal management. At all but two of the vulnerable locations, it is housing and infrastructure that is central to the sea-level rise risk, and whilst some of this is only at risk due to sea-level rise, most of it would be vulnerable even if the ocean was not rising. This is not to say that infrastructure and housing is the problem (this is clearly not the case), but to highlight the importance of applying diligence and caution in locating development. The City of Cape Town's coastal zone is dynamic and subject to climate change influences. Development that impedes the coastal equilibrium, and the shift in this equilibrium, invites economic and social risk. The OECD (2009) encourages "Climate conscious development"; the basis of this approach is based on an understanding that in an urban context the built environment defines the relationship between people and the natural environment. In the context of integrated coastal zone management and sea-level rise, the built environment should reduce and not amplify sea-level rise risks or transfer them to another location.

An interesting distinction arises when the type of coastal development is examined. The houses at Bakoven are vulnerable to wave run-up, wave set-up, due the hard nature of the coast and because houses have been built perilously close to the sea. The housing investment is, however, largely private and accordingly the City of Cape Town may not feel under any obligation to protect these houses but should ensure that any private measures undertaken to protect the houses is compliant with legislation. In contrast the infrastructure between Milnerton and the harbour is of public significance and includes an oil pipeline and a major feeder road for the City. In addition some of the coastal erosion in this region has been caused by the construction of the Cape Town port. Clearly both the infrastructure itself, the implication of the infrastructure being damaged and the potential liability is a public issue at this location and, unlike at Bakoven, should be prioritised for public attention.

Table 2: Combined risk caused by wave run-up, wave set-up, nature of coastline and extent of development at exposed locations around the City of Cape Town's coastline.

	Aggregate risk
Melkbosstrand	2
Blouberg (Bay)	2
Tableview beachfront	2
Milnerton beach	3
Milnerton to harbour	3
Green Point & Sea Point	3

Glen Beach	2
Camps Bay	3
Bakoven cottages	4
Kommetjie	3
Witsands	2
Glencairn	2
Fish Hoek dune section	1
Kalk Bay	3
Muizenberg corner	2
Strandfonetin – Baden Powell Drive / Treatment Works / Landfill.	3
Monwabisi and Macassar Pavilions.	3
Strand (entire beach front).	3
Bikini beach	2

Table 2 aggregates the different components of sea-level rise risks at different locations. The aggregation conceals important information, including information on that can be used to lower risk, but the aggregation does provide a sense of which locations are most exposed and most likely to require attention in the short term.

4. Adapting to sea-level rise

In the face of rising sea-levels, increasing frequency and intensity and of storm surges and pressure for coastal development, the challenge for the City of Cape Town is how to respond. Timely responses can reduce the cost of sea-level rise impacts, but responses themselves impose costs (Stern et al., 2006; Tol, 2006).

Responses to sea-level rise fall under the broad rubric of climate change adaptation. When climate adaptation concerns coastal zones the general consensus is that is that the best responses are location specific and take place under the remit of "integrated coastal zone management" (ICZM).[4] The conceptual merits of ICZM are seldom disputed, but for local decision makers the challenge remains how to apply this theory in the face of intractable trade-offs and difficult to quantify risks. Specific to this challenge are the uncertainties surrounding, the extent of expected sea-level rise events, the timing of sea-level rise events, and establishing acceptable levels of public risk ("how safe is safe enough?"). Inherent uncertainties regarding future concentrations of greenhouse gases (IPCC, 2007) let alone how these concentrations will translate into changes in atmospheric temperature and ocean dynamics, make these questions impossible to answer precisely. What is clear is that the level of certainty that has, in the past, been assumed with regards to sea-levels along the Cape Town coast, no longer applies. This necessarily has implications for development planning, insurance, investment and emergency relief.

3.1 Adaptation as a set of decisions

In a stylised sense the options available to the City of Cape Town can be illustrated as in Figure 3.

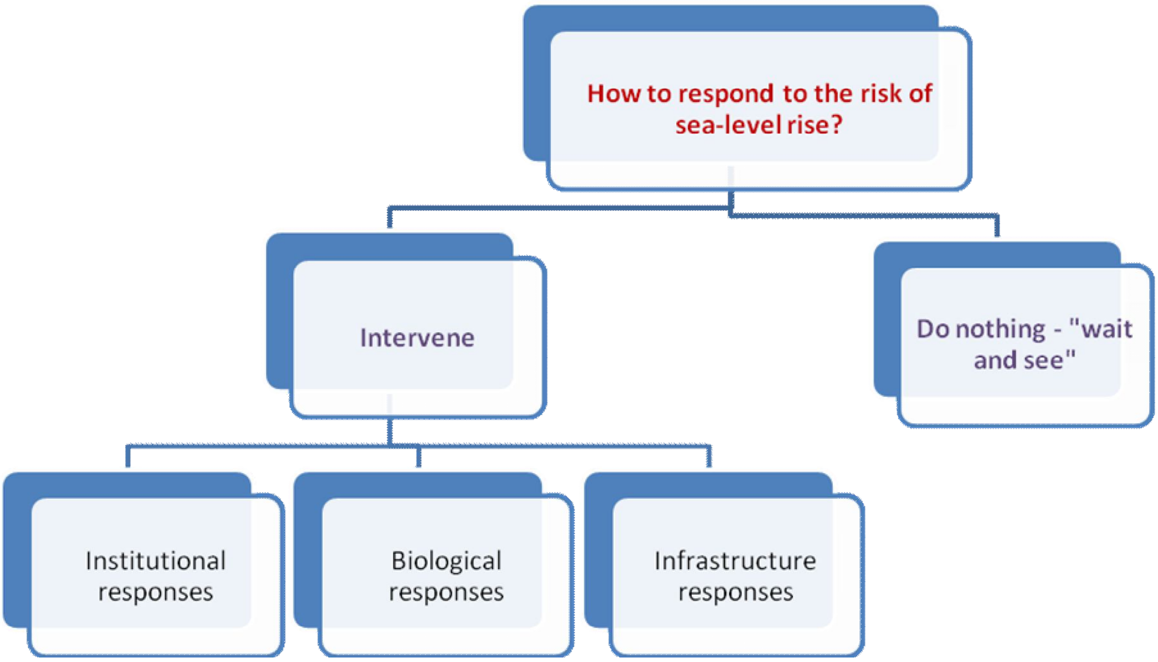

Figure 3: Options available in responding to sea-level rise risks.

The defining decision confronting the City of Cape Town is whether or not to do anything about sea-level rise at all. Adopting a "wait and see" approach is not as insouciant as it may

[4] ICZM aims to "Consider over the long term to balance environmental, economic, social, cultural and recreational objectives, all within the limits set by natural dynamics" (Commission of European Communities, 2000)

sound. Past interventions have not been particularly effective, a delay permits additional information to emerge on the nature of the threat - information that can be applied in crafting a more appropriate response. The City of Cape Town needs to avoid setting a precedent that will see it called upon to safeguard its coastline in an untenable number of cases. By intervening to ensure people's safety in the face of a sovereign threat, it is possible to promote moral hazard in the form of civil apathy or worse, a continuation of hazardous coastal development. The final, and often most relevant appeal of the "wait and see" approach lies in its avoidance of the costs that are often incurred in adaptation efforts. This cost avoidance, however, can represent a false economy. Stern et al. (2006) and SwissRe (2009b) emphasise that money spent avoiding climate change impacts in the immediate term, save much larger amounts of money required to deal with the consequences of these impacts. The merits of early action are both moral and financial, but where this ignored in favour of a "wait and see" approach there should at least be an increased investment in disaster relief capacity.

Assuming that something must be, the next decision involves selecting "what". Phase 4 of this study identified a range of options. The most attractive of these were considered "no regrets" in their nature; the sort of options that the City of Cape Town should be doing even if sea-level rise were not a threat, but which will reduce the risk of sea-level rise if implemented. These include not reclaiming additional land, protecting wetlands, estuaries and dune cordons from further degradation, maintaining drains and stormwater systems so as that they operate to their specifications and alleviating poverty so as to reduce exposure to a wide range of risks, including the risks imposed by sea-level rise.

The more difficult decisions lie in selecting options specifically aimed at countering the sea-level rise risk. Phase 4 classified options into:

- Infrastructure interventions – sea-walls, groynes, barrages and barriers, raising infrastructure, revetments, rock armour, dolosse and gabions, off shore reefs, beach nourishment, water pumps, beach drainage.
- Biological interventions – dune cordons with vegetation, estuary and wetland rehabilitation, kelp beds.
- Socio-institutional interventions – vulnerability mapping, risk communication, apply legislation (Coastal Development Guidelines, Integrated Coastal Management Bill, White Paper on Sustainable Coastal Management), apply a coastal buffer zone, prevent sand mining, research and monitoring, early warning system, heightened disaster management system and insurance market correction.

Different approaches to deciding on options are illustrated (below) by their application to the sea-level rise adaptation options identified in Phase 4 in the context of a known City of Cape Town "hot spot", the Milnerton Golf Club. The club is constructed on a sandspit between the Milnerton Lagoon and the sea. The affronting beach is protected from large wave erosion by Robben Island, but the construction of the Cape Town harbour and foreshore land reclamation have altered the near-shore currents so as to accelerate beach erosion at Milnerton. It is the coastal erosion caused by redirected long-shore currents and higher mean sea-levels to which the golf club is most exposed, although the lagoon on the landward side of the golf club exposes the building to the possibility of erosion from both sides. The local golf club is in currently in danger of being undercut and collapsing. The club's private efforts to protect its building have included sand bags and some beach replenishment, but these have not proven effective to date.

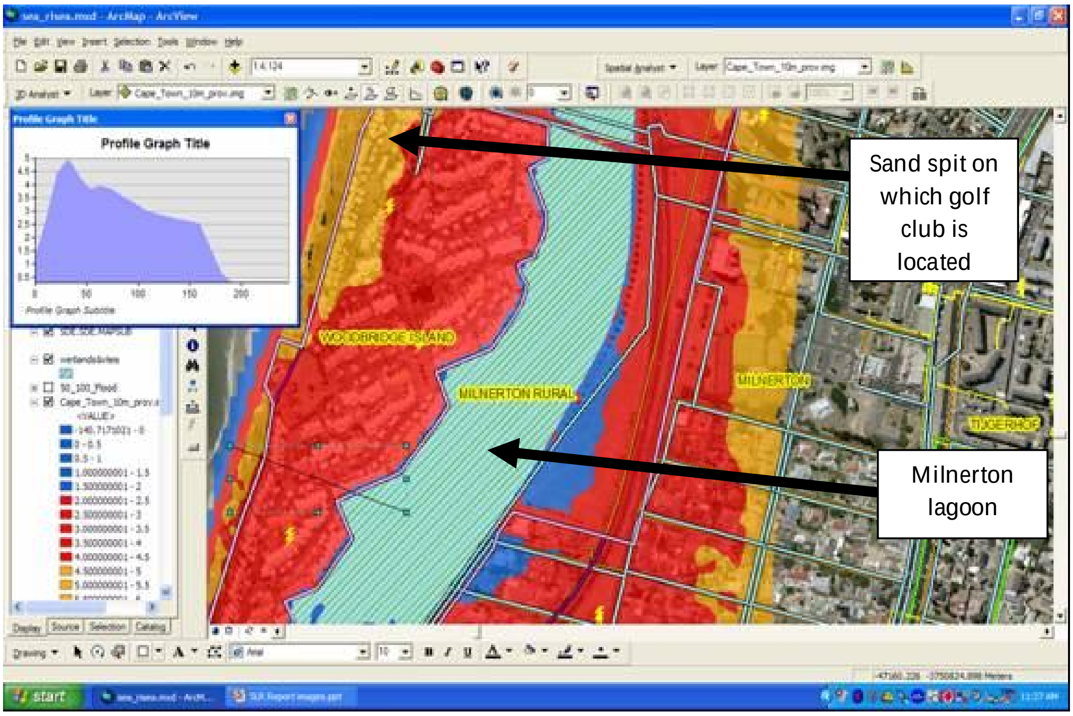

Figure 4: The Milnerton lagoon area close to where the Milnerton Golf Course is located showing the impact of a 2.5 metre (blue), 4.5 metre (red) and 6.5 metre (orange) sea-level rise increase, and the general exposure of the region to coastal erosion. (Source: Phase 2 of this Study).

3.2 Cost benefit analysis (CBA)

The conventional way of selecting adaptation options has involved cost benefit analysis (CBA) (Stern et al., 2006; Von Ierland et al., 2007; Hallegatte, 2008; SwissRe, 2009b); the options that save the greatest cost for the least expense are considered most desirable. Adopting this approach can be useful in securing financial and political support and CBA can be used - as demonstrated by SwissRe (2009b) - to distinguish between measures that:

- Are cost negative and therefore create savings, many of which are "no regret" options.

- Present economic benefits that outweigh the cost of implementation, and should be considered a prudent investment.
- Cost more than they save but which may be deemed necessary to protect human life, heritage or biodiversity.

A more interesting application for CBA involves its application in establishing long-term differences between biological, infrastructural and socio-economic options. Data and appropriate valuations remains a problem but when applied across a wide number adaptation options under different circumstances at different locations it becomes clear that generally (this is not always the case), socio-institutional options offer better returns than biological options, which offer better returns than infrastructural options (Figure 5 and 6).

There are, however, limitations to CBA. Typically the data required for such analyses are not available. It can be difficult to accurately assess both cost and benefits when the exact nature and timing of the threat is unknown, this type of analysis tends to treat options as discrete while in practice it is combinations of options that are likely to be most effective and there is subjectivity involved in valuing environmental goods and services and heritage products that are not traded in markets but recognised as being valuable in preventing sea-level rise impacts. Perhaps most critically CBA tends to suggest levels of precision and certainty in decision making that are not warranted, and even disingenuous, in the context of climate change impacts.

CBA can be useful as a decision support tool, but to apply it exclusively so as to attain some form of “financially optimal” solution to sea-level rise verges on hubris.

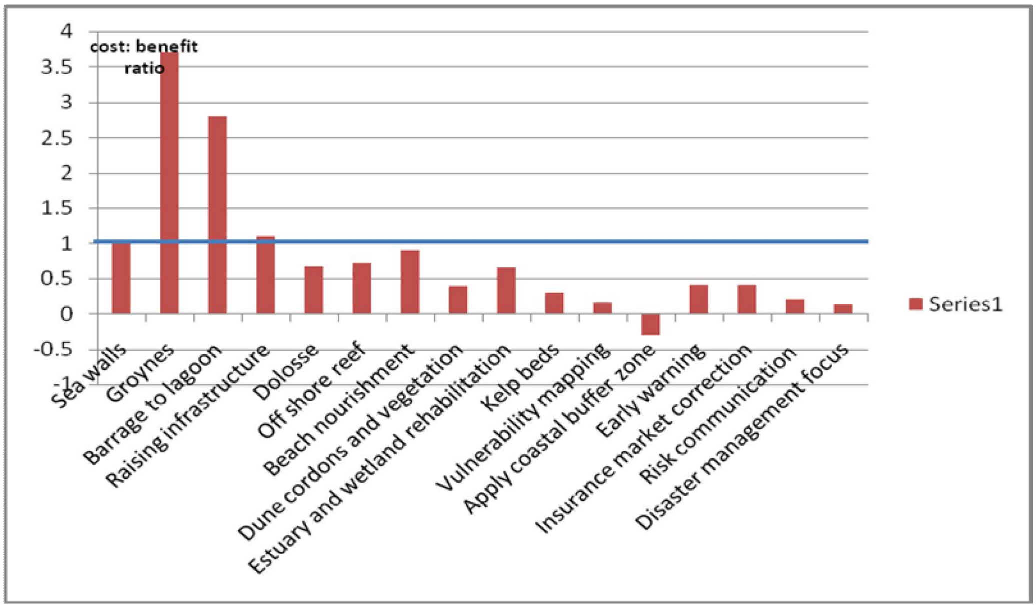

Figure 5: Hypothetical cost: benefit ratio for the adaptation options available to the Milnerton Golf Club (based on SwissRe (2009b)) estimates for sea-level rise damage in Florida. In practice it is difficult data to make these calculations and such efforts struggle to apply appropriate timeframes and values to costs and impacts. The analysis can be useful in showing that some options (those below the horizontal "zero" line) save money, some options (those below the blue line at 1) save more money than they cost, and some options (those above the blue horizontal line at 1) simply cost money.

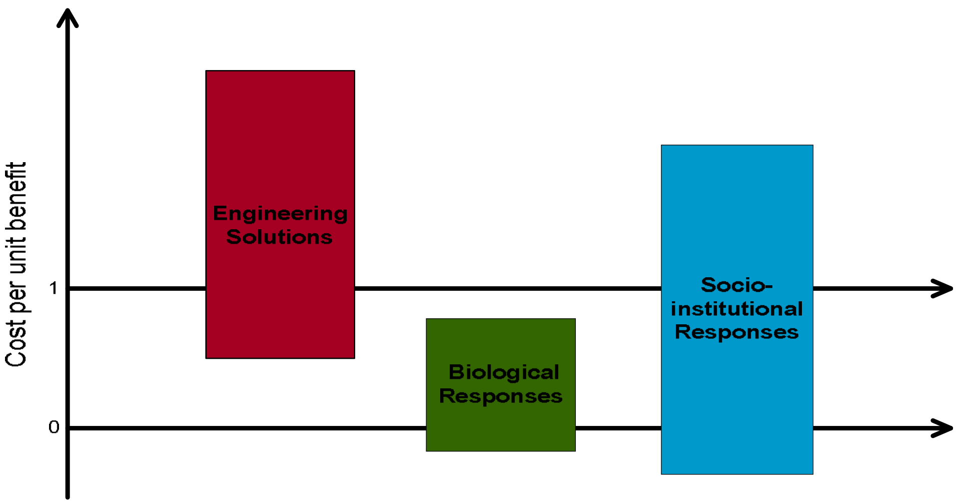

Figure 6: A stylised representation of the range of cost per unit benefit of general infrastructure (engineering), biological and socio-institutional adaptation options. (Source: Cartwright and Constable, 2009).

3.3 Multi-criteria assessment (MCA)

A more robust means of taking sea-level rise adaptation decisions involves subjecting options to a multi-criteria assessment (MCA). Under this approach options are interrogated in terms of an agreed upon set of assessment criteria, with the intention being to create multi-disciplinary consensus on the most appropriate course of action. Crucially MCA is well suited to create the type of institutional capacity that is required for effective climate change adaptation. Climate change adaptation theory emphasises the importance of "socio-institutional learning" (Downing et al. 2007), monitoring, reflexive institutions, ongoing decision making and iterative progress, all of which is more likely under MCA than CBA.

MCAs have been criticised for their subjectivity. The questions, "Who gets to select the criteria?" and "Who gets to perform the assessment?" are legitimate, but crucially MCAs of sea-level rise risks are capable of bringing together South Africa's particularly divergent development needs and integrating the needs of private land owners, local governments, provincial governments, various departments within national government and conservation authorities all of which have responsibilities towards Cape Town's coastline.

For the City of Cape Town the type of criteria that are relevant include:

- Risk reduction: The extent to which the options reduces risk of sea-level rise.
- Ease of implementation: Not all desirable responses are possible, either due to the institutional complexity involved in implementing them or their cost. In the case of the City of Cape Town, it is particularly important to identify who is responsible for the intervention and who will pay for the intervention. Options should be selected commensurate with capacity to deliver them effectively.
- Positive externalities: The extent of positive externalities associated with the option. Does the implementation yield, or make more likely, benefits that are not related to sea-level rise.
- Scope for mal-adaptation: Some options, and particularly infrastructural options, are more difficult to do well. Options should be selected cognisant of the need to avoid unintended negative consequences. This should include mal-adaptation arising uncoordinated private efforts.
- Cost: Budget constraints inform decisions and the extent of reduced impact per unit investment over the long term remains crucial.
- Greenhouse gas emissions: Options that involve large volumes of additional greenhouse gas emissions (beach pumping, cement structures) should be considered less suitable that those that do not.

- Reversibility and flexibility: Given that the precise extent and nature of sea-level rise impacts is not known, those options that can be reversed or altered as more information becomes available should be considered preferable.

- Retention of complementary options: Combinations of options tend to be more effective than single approaches but not all options permit complementary solutions. Those options that permit complementarily are favourable.

- Equality implications: Poor people tend to be more risk averse than affluent people. Cape Town remains a highly unequal society. The default when climate change interventions are not planned is for risk to be transferred to poor people who are least able to afford it or insure themselves against it. This will exacerbate Cape Town's inequality and underdevelopment. Effective adaptation options should be socio-economically progressive and where necessary transfer risk away from poor people.

MCAs are necessarily participatory activities, but by way of example a hypothetical application on the Milnerton Golf Course decision is conducted below.

Table 3: Multi-criteria assessment of sea-level rise options to support the Milnerton Golf Club.

	Risk reduction	**Positive externalities**	**Institutional complexity**	**Scope for maladaptation**	**Cost**	**Contribution to GHG mitigation**	**Reversibility and flexibility**	**Retention of complementary options**	**Equality implications**	**SUM**
Sea walls	2	1	1	1	1	1	1	1	1	10
Groynes	1	2	1	1	2	2	1	2	2	14
Barrage to lagoon	2	1	1	1	1	1	1	1	1	10
Raising infrastructure	1	1	2	1	2	1	1	1	1	11
Dolosse	3	1	2	2	2	1	1	1	2	15
Off shore reef	3	2	1	1	2	2	1	2	2	16
Beach nourishment	2	2	2	2	2	3	2	3	2	20
Dune cordons and vegetation	2	3	2	3	2	3	3	3	3	24
Estuary and wetland rehabilitation	1	3	2	3	2	2	3	3	3	22
Kelp beds	2	2	2	1	2	3	2	3	2	19
Vulnerability mapping	1	3	2	2	2	3	3	3	3	22
Apply coastal	3	3	1	3	1	2	3	1	3	20

buffer zone										
Early warning	2	3	3	2	3	2	3	3	3	24
Insurance market correction	2	2	2	2		2	3	3	2	18
Risk communication	1	3	3	2	3	2	2	3	3	22
Disaster management focus	2	1	3	3	2	2	2	3	3	21
Managed retreat	3	3	1	3	1	2	1	3	3	20

1= poor, 2= neutral / moderate, 3= excellent

MCAs are capable of producing more balanced and considered decisions than CBA, but like CBA they represent a decision support tool and should not be applied expediently. Certainly multi-criteria assessments do not provide a surrogate for good decision making. By applying quantitative scores to the options it is possible to get a sense of the relative merits of different options. The quantification should not, however, be exploited for inference purposes. In drawing inference, however, the distinction between a cumulative score of 18 and 19 should not be seen as the basis for decision making. MCAs are useful in identifying generally better options, and screening the options confronting decision makers. It is possible to refine the screen, scrutinise options under new criteria and even re-weight specific criteria that are deemed more important than others.

In the Milnerton example it becomes clear that infrastructural responses present problems on certain accounts: they tend to promote lock-in and hinder reversibility and flexibility, they present scope for mal-adaptation, they do not promote the use of complementary options, they protect only those that can afford to pay for the considerable cost and where infrastructure involves cement, it releases greenhouse gases. This finding concurs with the literature (Van Ierland et al., 2007; Hallegatte, 2008; SwissRe 2009b). There are specific instances – immovable assets such as harbours, or strategic infrastructure such as electricity substations - in which the use of infrastructure is essential and does represent the best option, but this tends to represent the last resort once other options have been exhausted. The MCA suggests that where infrastructure or engineering solutions are deemed necessary at Milnerton, beach nourishment, off shore reefs and possibly dolosse appear to be the most favourable options. Dune cordons with vegetation (if these can be adequately re-established and stabilised at this site) and an early warning system that triggers the placing of sandbags or simple evacuation and removal of valuable property are identifies as being suitable against a wide range of criteria. Where these options are shown to provide inadequate cover they can be easily complemented or enhanced. The same is not typically true of infrastructure approaches.

5. Conclusion

The City of Cape Town is at the forefront of developing country responses to climate change. Collectively, these responses involve an experiment as countries and cities grapple to establish workable solutions and guiding principles. In spite of the innovative nature of Cape Town's work, it is not the only country or institution to research or respond to sea-level rise risks: NASA's Goddard Institute[5], The United Nation's Environment Programme (UNEP), Climate Action Network International (CANI), Stockholm Environment Institute (SEI), the WeAdapt Partnership and eThekwini Municipality are among the other leaders in this field and there is some merit in exploring solution collectively.

This Phase 5 of the City of Cape Town's Sea-level Rise Risk Assessment study advanced the work undertaken in Phases 1-4 by exploring the detailed nature sea-level rise risks along the City's 307 kilometre coastline (including conservation areas).

The study highlights the location specific nature of sea-level rise events and distinguishes areas in terms of their exposure to mean sea-level, wave set-up and wave run-up, respectively whilst also including the "hardness" and "softness" of the coastline and the extent and nature of coastal development . Given that the phrase "sea-level rise" is used to describe an increasing variety of events, this distinction is central to gaining a better understanding of the nature of sea-level rise threats and allows monitoring and early warning systems to be tailored for specific locations.

The study supports the notion that the level of certainty that has been applied in the past with regards to sea-levels, no longer applies. Whilst sea-levels at Cape Town appear to be rising in line with the global mean, and the IPCC expects this mean to have increased by 0.18 – 0.59 metres by the end of the 21st Century, inherent uncertainty still defines projections and the evidence in support of far greater and more rapid increases appears to be mounting. Even small increases will cause disproportionately large impacts, especially where they are compounded by more intense (and possibly more frequent) storm events, as is expected.

A great deal of sea-level rise risk can be removed by timely interventions, but deciding exactly how to respond and who should take responsibility and pay for responses is complex. The nature of sea-level rise risks is subjective. The same risks affect different people in different ways and there is no single "socially acceptable" level of risk or loss, particularly where loss of life and private property is involved. The complex nature of sea-level rise risks make it inappropriate to leave the defining pronouncements and selection of adaptation measures on this matter, to either economists using CBA or actuaries applying risk calculation instruments. The need is for what SwissRe (2009b) term a "risk consensus"; a general agreement on the

[5] National Aeronautical Space Administration.

nature of sea-level rise risks and how this risk should be most appropriately shared in the context of other development goals.

This study applied a illustrative CBA and MCA to the adaptation options available to protect a known City of Cape Town sea-level rise hotspot, the Milnerton Golf Course. It is proposed that a multi-criteria assessment, provided the selection of criteria and assessment can be performed in a participatory manner, represents a more appropriate means of ensuring consistent and effective sea-level rise adaptation decisions in the long term.

Reference list

Bengsston, L, Hodges, K and Roecknet, E (2006) Storm Tracks and Climate Change. Journal of Climate 19, pp. 3518-3543.

Bindschadler, R (2006) Hitting the Ice Sheets Where it Hurts, Science 24 March, Vol. 311. no. 5768, pp. 1720 – 1721, DOI: 10.1126 / science.1125226.

Brundrit, G (1995) Trends in Southern African sea level: statistical analysis and interpretation, South African Journal of Marine Science, vol. 16, pps 9-17.

Brundrit, G (2008) Global Climate Change and Adaptation – a sea-level rise risk assessment. Phase 1: Assessments of sea-level rise for the City of Cape Town.

Brundrit, G, Cartwright, A and Fairhurst, L (2008) Global Climate Change and Adaptation – a sea-level rise risk assessment. Phase 1: Assessments of sea-level rise for the City of Cape Town. Executive Summary Phases 1-4.

Brundrit, G (2009) Global Climate Change and Adaptation – a sea-level rise risk assessment. Phase 5: Full investigation of alongshore features of vulnerability on the City of Cape Town coastline, and their incorporation into the City of Cape Town Geographic Information System (GIS).

Cartwright, A (2008) Global Climate Change and Adaptation – a sea-level rise risk assessment. Phase 4: Sea-level rise adaptation and risk mitigation measures for the City of Cape Town.

Cartwright,A; Constable, L (2009) eThekwini Municipal Adaptation Plan; health and water. Municipal Climate Protection Programme: eThekwini Municipality.

Commission of the European Communities (2000), Communication from the Commission to the Council and the European Parliament on Integrated Coastal Zone Management: a Strategy for Europe (COM/2000/547/Brussels)

Downing, T. E., Cartwright, A and Smith, B (2007) Defining the Food and Agriculture's Role in Climate Change Adaptation. Report in partial completion of the compilation of FAO's Climate Change Adaptation Strategy. Available at: http://www.fao.org/climatechange/home/en/

Hansen, J (2007) Scientific reticence and sea-level rise. IOP Environmental Research Letters. Available at http://www.iop.org/EJ/article (Published 24 May 2007).

Hallegatte, S (2008) Strategies to Adapt to an Uncertain Climate Change. Global Environmental Change, 684, pp. 8.

IPCC (Intergovernmental Panel on Climate Change) (2007) Fourth Assessment Report (AR4), Synthesis Report, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 20 pp. Available at www.ipcc.ch

Kana, T; Michel, J; Hayes, M and Jensen, R (2005) The Physical Impact of Sea-level Rise in the Area of Charleston, South Carolina. Climate Change 52(1–2):65–91.

Krabill, W, Hanna, E, Huybrechts, P, Abdalati, W, Cappelen, J, Csatho, B, Frederick, E, Manizade, S, Martin, C, Sonntag, J, Swift, R, Thomas, R and Yunge, J (2004) Greenland Ice Sheet: increased coastal thinning. Geophysical Research Letters, 31: L24402, doi:10.1029/2004GL021533.

OECD (2009) Kamal-Chaoui, Lamia and Alexis Robert (eds.) (2009), "Competitive Cities and Climate Change", OECD. Regional Development Working Papers N° 2, 2009, OECD publishing.

Lambert and Fyfe (2006) Changes in Winter Cyclone Frequencies and Strengths Simulated in Enhanced Greenhouse warming Experiments: results from the models participating in the IPCC diagnostic exercise. Climate Dynamics 26, pp. 713-728.

MacDeevit, C and Hewitson, B (2007) Sea-level Rise on the Cape Coast. Atmospheric Science Working Paper produced after Honours Thesis 2007. Climate Systems Analysis Group, University of Cape Town.

Mather, A (2007) Coastal Erosion and Sea-level Rise: are municipalities ready for this? Internal Document, eThekwini Municipality, KZN, South Africa.

Nicholls, R., and Tol, R. (2006) Impacts and responses to sea-level rise: a global analysis of the SRES scenarios over the twenty-first century. Philosophical Transactions of the Royal Society, A, 364 (1841): 1073-1095.

Nicholls R, Tol R, Vafeidis, A (2008) Global estimates of the impact of a collapse of the West Antarctic Ice Sheet. Climate Change (special issue).

Revkin (2009) Northern Sea Route Through the Arctic Becomes a Reality. New York Times, 28 July, 2009.

Rignot, E. and Kanagaratnam, P. (2006) Changes in the velocity structure of the Greenland Ice Sheet. Science, 311: 986-990.

Schumann, E and Brink, K (1990) Coastal-trapped waves off the coast of South Africa: Generation, propagation and current structures. Journal of Physical Oceanography 20:1206–1218.

Siddall, M; Stocker, T and Clark, P (2009). Constraints on future sea-level rise from past sea-level reconstructions. Nature Geoscience, DOI: 10.1038/NGEO587.

Smith, A; Guastella, L; Bundy, S and Mather, A (2007) Combined marine storm and Saros spring high tide erosion events along the KwaZulu-Natal coast in March 2007. South African Journal of Science, 103: 274.

Stern, N., S. Peters, V. Bakhshi, A. Bowen, C. Cameron, S. Catovsky, D. Crane, S. Cruickshank, S. Dietz, N. Edmonson, S.-L. Garbett, L. Hamid, G. Hoffman, D. Ingram, B. Jones, N. Patmore, H. Radcliffe, R. Sathiyarajah, M. Stock, C. Taylor, T. Vernon, H. Wanjie, and D. Zenghelis (2006), Stern Review: The Economics of Climate Change, HM Treasury, London.

Swiss Re (2009) Influence of Global Warming on Extra-Tropical Storms. Climate Change Facts Compiled by ProClim. Available online at: http://www.swissre.com/resources/

SwissRe (2009b) Shaping Climate Resilient Development; a framework for decision making. Report of the Economics of Climate Adaptation Working Group.

Tol, R (2006) The Stern Review of the Economics of Climate Change: a comment, November 2, 2006. Available at: http://www-iam.nies.go.jp/aim/stern/Tol_sternreview.pdf

Tol, R; Klein, R & Nicholls, J (2008) Towards Successful Adaptation to Sea-level Rise Along Europe's Coast. Journal of Coastal Research, 24(2), pp. 432-442.

Turpie (2004) South African National Spatial Biodiversity Assessment 2004: Technical Report. Estuarine Component. Pretoria. South African National Biodiversity Institute.

United Nations Environment Programme (UNEP) (2009) Year Book 2008/9. Available at: http://www.unep.org/geo/yearbook/yb2009/

Van Ierland, E, de Bruin, K; Dellink, R and A. Ruijs (2007) A Qualitative Assessment of Climate Adaptation Options and Some Estimates of Adaptation Costs. Study performed within the framework of the Netherlands Policy Programme. ARK as Routeplanner projects 3, 4 & 5, Wageningen University.

Velicogna, I. and Wahr, J (2006). "Measurements of Time-Variable Gravity Show Mass Loss in Antarctica". Science 311 (5768): 1754-1756. vol 5, pp 107–140.

Appendix A: Terms of Reference for Phase 5 study

The primary objective of this study is to improve understanding of the extent and manner in which City of Cape Town's coastline is likely to be impacted by sea level rise.

It is propose to achieve this by adding the influence of local factors such as offshore bathymetry, storm direction and coastal geography to the sea level rise model developed in Phases 1-4, and by including an understanding of how the various influences on sa-level rise interact with each other at a specific locations and over time.

Realising this primary objective rests on the incorporation of data pertaining to:

- Knowledge of the offshore wave climatology.
- The detail of the coastal bathymetry and its influence on wave run up.

Both these data are limited by the resolution of available observations. This appears to be recognised in the Terms of Reference by the restriction of the wave directions to the coarse compass directions NW, W, SW, S and SE. The course resolution will place constraints on the type of model and the accuracy of the results that can be expected from such models. Nevertheless, it should be possible in this Phase 5 to achieve the outcomes asked for in the Terms of Reference, namely:

- Develop a finer scaled and more accurate approach to the existing GIS model by identifying areas at risk due to a uniquely varying shoreline, bathymetry and coastal geography;
- Apply five storm direction scenario's to the City's coastline (NW, W, SW, S and SE);
- Identify key risk areas for each storm direction scenario based on swell direction, bathymetry, shoreline, swell shadows and coastal geography, and
- Improve the level of accuracy in the predictions for sea level rise events

Once these key risk areas have been identified, further observation programmes at a greater resolution can be contemplated, with a view to obtaining more predictive capability from the use of sophisticated inshore wave models.

The approach proposed for this study is to add to the factors in the existing GIS to enable impact variability along the coast to be assessed and predictability improved. The following aspects will be investigated:

- Swell dynamics i.e. characteristics of swell direction;

- Correlations that may exist between the various swell characteristics i.e. average wave height and wave length may be associated to a particular swell direction, time of year, wind direction, weather pattern etc;
- Coastal areas that will receive specific swell head-on, and those that will be sheltered from swell based on the five different storm direction scenarios;
- Critical coastal bathymetry. Shallow offshore banks will play a significant role in reducing swell energy reaching the coast whereas deeper near-shore bathymetry will result in increased wave energy reaching the coast;
- The effect of coastal geology and topography on hinterland vulnerability (sandy shore vs rocky shore)
- The direction and dynamics of longshore drift;
- The presence, state and influence of other natural barriers i.e. kelp forests in terms of reducing the impacts of storm swell and in which areas;
- The physical composition of the beach: A combination of rocks and sand tends to be more susceptible to erosion, and
- Vulnerable areas as a result of human development and activity.